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CONTENTS.

PAGE

Generation, Distribution, and Use of Electricity on Board Ship.
C. WALLACE SAUNDERS, H. W. WILSON, and R. G. JAKEMAN, D.Sc. 241

Power Stations and their Equipment (Progress Review) .... I. V. ROBINSON, Wh.Sc. 289

Copper Losses in Large Cables at Power Frequencies (E.R.A. Report) 299

Some Notes on Rates of Rise of Restriking Voltage Subsequent to Interruption of Alternating-Current Power Circuits ....C. H. FLURSCHEIM, B.A. 323

Discussion on "The Inherent Instability of Synchronous Machinery" 337

Discussion on "Research in the British Post Office" 339

Meter and Instrument Section: Chairman's Address ......Prof. J. T. MACGREGOR-MORRIS 341

Proceedings of the Institution 345

Institution Notes 346

Advertisements ....At end i–xiv

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GENERATION, DISTRIBUTION, AND USE OF ELECTRICITY ON BOARD SHIP.

By C. WALLACE SAUNDERS, Associate Member, H. W. WILSON, Associate Member, and R. G. JAKEMAN, D.Sc., Member.

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SUMMARY.

Brief consideration is given to the problems involved in the use of electricity on board merchant ships. The applications of electricity to warships, whilst very extensive, are considered to be outside the scope of the paper.

The various systems of generation in use, and considerations governing their adoption in individual cases, are outlined.

The nature and situation of the services comprising the load are discussed, with special reference to the electrical equipment of (1) a large turbo-electric liner, (2) a Diesel-propelled intermediate liner, (3) a Diesel-electric tug, and (4) a large cargo vessel carrying refrigerated cargo.

Particular reference is made to the refrigeration equipment of vessel (4), on account of its importance, and of the advantages offered in this sphere by electrical operation.

The present position of electric propulsion is discussed, together with the probable future developments in this field.

TABLE OF CONTENTS.

Introduction.

Part 1. Generation.
  Types of vessel, and nature of load.
  Types of generator and systems of supply.

Part 2. Distribution and Use.
  Switchboards.
  Engine-room auxiliaries.
  Hull machinery.
  Refrigeration machinery.
  Ventilation.
  Deck machinery.
  Motor starters and controllers.
  Motor design.

TABLE OF CONTENTS—*continued.*

  Hotel load.
  Cables.
  Miscellaneous equipment.

Part 3. Electric Propulsion.
  Choice of system.
  Turbo-electric drive.
  Direct-current Diesel-electric drive.

Conclusion.

INTRODUCTION.

Nowadays when the design and construction of a new vessel are under consideration the use of electricity for auxiliary purposes is taken as a matter of course. Its use for propulsion purposes is also in many cases given very serious thought.

Electricity has been used in the British Navy for various purposes since 1874, but although in the merchant service it has been used for lighting for many years it is only since the advent of the Diesel engine and the consequent elimination of steam from a large number of vessels that electricity has been used extensively for other purposes. To-day almost all auxiliary machinery —from the windlass in the bows, through the engine room and hull, to the steering gear in the stern—is, in most important ships, electrically operated.

Great progress has been made with electric propulsion both in this country and abroad, and in 1931 the power of the electrically-propelled ships of all nationalities exceeded 1 000 000 s.h.p. British yards alone turned out during 1931 first-class passenger-carrying tonnage totalling 70 000 s.h.p. Table 1 gives details of the more important of these vessels.

TABLE 1.

Name of vessel	Owners	Propulsion generators	Propulsion motors	Auxiliary generators	Gross tonnage
Strathnaver*	Peninsular and Oriental Steam Navigation Co.	2 turbines, 10 700 kW each	2 3-phase synchronous, each 14 000 s.h.p.	3 turbines, 750 kW each 1 turbine, 400 kW	22 540
Strathaird* . .	Peninsular and Oriental Steam Navigation Co.	2 turbines, 10 700 kW each	2 3-phase synchronous, each 14 000 s.h.p.	3 turbines, 750 kW each 1 turbine, 400 kW	22 540
Rangatira* . .	Union Steam Ship Co. of New Zealand	2 turbines, 5 300 kW each	2 3-phase synchronous, each 6 750 s.h.p.	3 turbines, 350 kW each	6 152
Monarch of Bermuda*	Furness, Withy, and Co.	2 turbines, 7 500 kW each	4 3-phase synchronous, each 4 750 s.h.p.	4 turbines, 750 kW each	22 424

* Built by Messrs. Vickers-Armstrong, Ltd.

Since 1931, shipbuilding has suffered, in common with most other industries, from the prevailing depression. Nevertheless, the largest vessel turned out in 1933, namely the " Queen of Bermuda," is electrically propelled.

When the type of propelling and auxiliary machinery is under review the following requirements (in addition to those of efficiency and first cost) must be studied in all their aspects. (*a*) The available space must be utilized to the greatest advantage. (*b*) The machinery must withstand the arduous conditions of marine service at a minimum cost for maintenance. (*c*) The vessel must be capable of being quickly manœuvred in and out of its berth, making a fast run from port to port with sufficient reserve of power to enable it to make up time lost through bad weather or on account of a late start due to delays in connecting services. It must be capable of a quick turn-round at each end of the voyage.

A passenger liner may be required to spend a certain portion of its life in cruising at reduced speeds, and during the regular voyage to maintain a varying speed schedule over sections of the run.

On certain types of cargo vessels the amount of power required for auxiliary purposes and cargo handling may be very large, amounting to an appreciable percentage of that required for propulsion.

In the large insulated holds of vessels carrying refrigerated cargo, often exceeding in value that of the ship itself, it may be necessary to maintain the temperature constant to within 1 deg. F. throughout the voyage.

That electrical operation can satisfactorily fulfil all of the demands made by these services is an established fact.

Part 1. GENERATION.

Types of Vessel, and Nature of Load.

The various types of vessel in service may be roughly divided as follows:—

Large passenger liners.—These may include the largest ships afloat. Electrical power may be used for propulsion, and nowadays is almost invariably used for all auxiliary purposes, e.g. hull machinery, engine-room machinery, lighting, heating, cooking, and ventilating.

Intermediate liners.—These comprise combined cargo and passenger vessels which employ Diesel engines, geared turbines, or steam reciprocating engines, for propulsion, and electrically-driven auxiliaries, electric lighting, etc.

Large cargo vessels.—These may be propelled by geared turbines, steam reciprocating engines, or Diesel engines, and carry an enormous amount of refrigerated cargo. The refrigeration equipment, and most of the other auxiliary services such as lighting, are practically always electrically operated.

Small cargo vessels.—These include self-unloading vessels (which are also sometimes electrically propelled). All have electric lighting, and in most cases the auxiliaries are electrically operated.

Tugs and small craft.—In vessels of this type electric lighting is employed, and electric propulsion is becoming extensively used.

Trawlers.—These provide an extensive field for the increasing use of electricity for all purposes. Some trawlers are already equipped with electric trawl winches and electric lighting.

It is literally true that the electrical equipment of a modern ship covers practically the whole range of present-day electrical products. Table 2 gives details of the numbers, types, and duties, of the electrical machines and apparatus installed in a typical 20 000-ton passenger liner.

Types of Generator and Systems of Supply.

The following types of generator and systems of supply are generally adopted.

For propulsion: turbo-electric alternating-current; Diesel-electric direct-current; exhaust turbo-electric alternating-current and exhaust turbo-electric direct-current for extra power; Diesel-electric extra power in vessels propelled solely by Diesel engines, for electric starting and manœuvring of main engines to " slow ahead " and " slow astern."

For auxiliary purposes: geared turbo-electric direct-current; Diesel-electric direct-current; steam reciprocating sets direct-current.

For turbo-electric a.c. propulsion, 3-phase turbo-alternators running at 3 000 r.p.m. are generally employed. The supply voltage may be as high as 10 000 volts, but is usually about 3 000. The alternators are as a rule provided with closed-circuit coolers, sea water being circulated as the cooling medium. In order to minimize trouble due to condensation whilst the alternators are not in use, small electric heaters of from 2 to 3 kW capacity may be embodied in the frames of the machines. Excitation is obtained from the ship's auxiliary supply via either negative boosters or motor-generator sets.

In the case of Diesel-electric d.c. propulsion, the voltage may be as high as 1 200 or 1 500 volts. In large installations there are usually several generators in series, and double-armature motors are employed. The main generators are normally connected in series with the double-armature propelling motor, but switching means are provided so that in the event of a generator or half-motor being out of commission for any reason the unit in question can be isolated and the vessel may proceed at reduced speed.

The question of drive for auxiliary generators naturally depends largely upon the type of propelling machinery in use. In cases where steam is used for propulsion, the auxiliary generators may be steam-driven also. There is much to be said, however, for Diesel-driven auxiliaries even if steam is used for propulsion, as the Diesel-driven sets can be run at any time whether the boilers are in use or not.

The auxiliary generating plant may vary from several 1 000-kW generators for a large liner to a 1-kW lighting set for small craft. The generators are usually compound-wound, and arranged for parallel running.

Where Diesel-driven generators are employed for propulsion the auxiliary generators are usually run in tandem, i.e. coupled to the same shaft as the propulsion generators, and equipped with automatic voltage regulators. The auxiliary generators supply excitation in addition to the auxiliary power and lighting load.

If the main engines are of the direct Diesel type Diesel-

TABLE 2.

Details of Electrical Machines Installed on a 20 000-*Ton Turbo-Electric Passenger Liner.*

Duty	Type	Number	Total h.p.	Remarks
Propelling machinery	Turbo-alternators	2	20 100	3 000-volt
	Propelling motors	4	19 000 s.h.p.	
	Ventilating fans	4	84	For propelling motors
Dynamos	Boosters	3	125	For excitation
	Main generators	4	4 020	220-volt, direct-current
	Emergency generators	1	67	
Pumps	Main circulating	2	320	
	Auxiliary circulating	3	195	
	Bilge, ballast, sanitary, and general service	6	144	
	Main extraction	2	50	
	Auxiliary extraction	3	21	
	Sludge	1	4	
	Forced lubrication (oil)	2	13	
	Heeling tank	2	16	
	Hot fresh water	1	2¼	
	Laundry and swimming bath	2	1	
	Cooled water	1	1¼	
	Fresh water	2	36	
	Oil-fuel transfer	2	54	
	Cargo fresh water	1	18	
	Watertight doors	2	10	
Steering gear	Steering-gear motors	2	84	
	Auxiliary steering-gear motors	1	7½	
Deck machinery	Windlass motor	1	150	
	Windlass booster	1	90	
	Capstan motors	4	300	
	Capstan boosters	4	236	
	Winch motors	4	96	
	Baggage winches	2	14	
	Warping winch	1	7	
	Boat davits	8	120	
Fans	Forced draught	8	136	
	Engine-room ventilation	9	122	
	Accommodation ventilation	104	248	
Refrigeration	Compressors	4	220	
	Brine pumps	5	40	
	Circulating pumps	4	16	
	Miscellaneous	12	10	
Laundry	Washing and ironing machines, etc.	7	15	
Lifts	Variable-voltage motor-generator sets	4	26	
	Passenger lifts	3	31½	
	Engineers' lifts	1	5	
	Stores, cargo, and service lifts	7	56	
General	Sewage compressors	2	110	
	Dancing-space dimmer	1	12 kW	
	Miscellaneous	21	70	
	Cabin fans	650	—	Fractional h.p.

driven auxiliary sets are employed. Ships of this type have been equipped with waste-heat boilers heated from the main engine exhaust, combined with a steam-driven auxiliary generator.

In order to supply power when the auxiliary generators are not running, a small direct-driven set is usually installed. To meet Board of Trade requirements on passenger ships a small internal-combustion engine driven generator called the " emergency generator " is installed also, always on an upper deck.

Constructional Features of Generators.

In the main constructional features, generators for use on board ship follow the practice which has been adopted for land work and which has proved successful for many years.

Particular care has to be given to the design from the point of view of accessibility and facility for overhaul, on account of the limited head-room and space available.

All machines must be specially impregnated to withstand tropical conditions. Protection must be afforded against dripping moisture.

The generators may have to run in a fume-laden or oil-vapour-laden atmosphere, and—particularly in the case of d.c. machines—it is necessary for the design to be so arranged as to prevent the accumulation of dirt and oil at inaccessible points where they can lie unsuspected and eventually lead to failure.

As a.c. generators for propulsion may run for prolonged periods at any speed from dead slow to full, critical speeds must be avoided within this range.

Lubrication must be arranged to function satisfactorily at all speeds and with a roll or list of 22½°. The utmost possible freedom from noise and vibration is essential.

Unfortunately, perhaps, from the point of view of an ideal engineering lay-out, the machinery spaces are usually cut down to an absolute minimum: the design must therefore of necessity be as compact as is compatible with the foregoing requirements. Naval architects and consulting engineers can assist materially in this direction by ensuring that the machinery spaces are adequate and are efficiently ventilated and illuminated.

Auxiliary Supply.

The auxiliary supply for power and lighting may be at either 110 or 220 volts, and in some cases 440 volts for power purposes. Direct current has been almost universally employed for auxiliary purposes, even in vessels where alternating current is used for propulsion. Alternating current has in a few cases been tried, but so far there has been no great tendency towards its general use.

Part 2. DISTRIBUTION AND USE.

SWITCHBOARDS.

The main generators and feeders are generally controlled from a main switchboard (Fig. 1) situated in close proximity to the generators, and ring-main feeders are taken to the various sub-switchboards throughout. It is usually necessary for the load to be divided deck by deck, and provision must be made for alternative supplies to essential circuits.

It must be appreciated that certain services such as emergency lighting, steering gear, lubricating-oil pumps, and refrigerating machinery, must be maintained at all costs. The circuits are therefore divided at the main switchboard into two categories—essential and non-essential.

Protection is afforded by means of a non-essential tripping system. In one form of this, auxiliary tripping busbars are run throughout the main switchboard, these busbars being energized through time-delay relays. In the event of an overload on the main dynamos, a contact is made through an overload relay. If the overload is maintained for, say, 2 sec., a time-delay relay makes its tripping contact and one set of tripping busbars is energized. This trips all the circuit breakers connected to this particular set of busbars, and all non-essential circuits are thus disconnected. Should the overload persist, a second time-delay relay operates on a second set of busbars after a further 2 sec., and all circuits of secondary importance become disconnected, only vital circuits being left alive. If the overload is still maintained after a further 2 sec., another time-delay relay will trip out the generator circuit-breakers, and, of course, the remaining circuits with them. It is of interest to note that the adoption of this or a similar scheme may effect a considerable saving in running costs, as the generators can be safely run at about full load capacity without endangering the continuity of supply to essential services. Consequently a smaller number of generators can be in use at any particular time, and those in use operate at maximum efficiency.

The generator circuit-breakers are usually equipped with overload and reverse-current protection, the former arranged to operate at a high value in case of a serious short-circuit (which would in any case render impossible maintenance of the supply), and the latter protecting against a failing engine or generator.

Sub-switchboards are installed where required throughout the ship, to allow of economy in cabling. A sub-switchboard should always be installed in the refrigeration engine room because it is desirable, owing to the fine limits of speed variation required, that the control of the compressors, brine pumps, and circulating-water pumps, should be placed in the most convenient position in order to facilitate ease of operation by the refrigeration engineers.

ENGINE-ROOM AUXILIARIES.

Engine-room auxiliaries (see Plate 1,* Fig. 2) comprise pumps, compressors, and fans, most of which have to function with unfailing reliability throughout the voyage, often in temperatures varying between zero and 140° F. In view of the possible high ambient temperature it is desirable that the rating should be very liberal.

Vertical-spindle centrifugal pumps are generally used in most modern ships, and there is much to commend this type of machine. It occupies a minimum of space, is easily protected from dripping moisture, and is readily accessible.

HULL MACHINERY.

A large proportion of the hull machinery, such as lifts, fans, and ventilating units, is situated in close proximity to either the passenger accommodation, the navigating bridge, or the wireless room. Hence it will be readily understood that the greatest requirement apart from reliability is the maximum possible freedom from noise, vibration, magnetic hum, and inductive interference. Modern well-designed machines are quite capable of attaining a satisfactory standard in these respects, but it is desirable for the shipbuilder to co-operate to this end and to see that all cable runs are arranged to transmit as little interference as possible. These points are discussed in fuller detail later in this paper, in the sections dealing with " motor design " and " cables."

The steering gear is usually of the electro-hydraulic or the all-electric type, and on large ships the driving motors are usually arranged in pairs. Thus there is always one machine available for stand-by, although in close waters both machines may be and should be run together.

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* Facing page 256.

In addition to the above, a smaller machine run off the battery is sometimes installed. This can be arranged to start up automatically the instant the main steering-gear motors shut down, and its capacity is such that it will give steering facilities for a few minutes until the way is off the ship.

REFRIGERATION MACHINERY.

The problem of the control of refrigeration machinery is a very delicate one, and electrical operation offers many distinct advantages in this sphere. On some of the large cargo ships the refrigerating equipment is of particular interest on account of its size and of the fine degree of control which can be obtained.

The electrical installation may consist of, say, three 145-h.p. compressor drives together with brine and water circulating-pump motors and control gear. The compressors have to be run at full power before cargo is loaded, in order to cool down the cold-storage accommodation. During the voyage they are run at a very low speed to maintain the low temperature.

To meet these requirements a speed range (too great for shunt control) varying from 375 r.p.m. to practically zero is necessary. Series regulation has been used in the past, but the power dissipated in resistances is very considerable over a long voyage. An alternative arrangement, giving superior power economy for a greater speed range, is to employ a negative booster in series with the main motors, thus reducing the power otherwise wasted in heat. This method has been adopted with great success; speed control can be effected to the finest degree by varying the booster field. Consideration of price, weight, and space, may demand a single booster set capable of serving any of the three compressors. Moreover, the booster has to be cut in or out of any compressor-motor circuit without shutting down that machine and without varying the speed of any of the others. This is carried out by means of a change-over contactor panel common to all three motors and embodying an automatic starter for the booster set.

VENTILATION.

The ventilation of a ship presents one of the most fascinating and intricate problems with which engineers have been called upon to deal. In addition to the natural difficulties arising from the maintenance of an equable temperature under climatic conditions varying from arctic to tropical (sometimes in a few hours), the whims of individual passengers have to be studied and catered for. The latter are met by a small cabin fan, gyrating or not at will, whilst the general ventilation comprises pure air supplied by fans on deck through adjustable louvres and warmed as desired.

DECK MACHINERY.

The deck machinery includes windlasses, capstans, winches, lifeboat and gangway hoists, etc. The use of electricity for deck auxiliaries is a comparatively modern development, coincident with the evolution of the Diesel-driven ship. The duties which such equipment is called upon to face are among the most arduous which could be required of any type of machinery. Deck auxiliaries are subjected to rapid changes of temperature, are sometimes totally immersed in sea water, and are liable to be damaged by falling or swinging weights. Great skill is therefore necessary in their design to enable them to carry out their duties. Their operation, particularly in the case of winches, is always in unskilled hands, and they must be capable of control to within very fine limits in order to avoid damage to personnel, cargo, and the ship itself.

Windlass.

The windlass is used to lift and house the anchor and to warp the ship. It must be capable of breaking the anchor out of the mud, raising it quickly, and housing it gently in the hawse pipe without damage to the bows of the ship. It therefore follows that during these operations, and when warping ship, a strong pull is required at low speeds. Ability to stall at any stage and to maintain this pull when stationary, and a quick "get-away" when hauling slack, are also essential.

Windlass and Capstan Control.

Contactors with drum control have proved satisfactory for large and medium powers. Creeping speeds can be arranged by means of either series resistance or an armature diverter, and these features, together with a magnetic brake of disc or solenoid type and a slipping clutch, ensure that the load is always well under control.

Constant-current control has similar advantages to contactor control, but special generators are required and full-load current has to be carried throughout the system while it is working; consequently the machines are correspondingly large.

Ward–Leonard control is almost ideal for deck machinery, but the motor-generators in use with this system are both costly and bulky, and for this reason its use is somewhat restricted.

Booster control is a development of the Ward–Leonard system. It has most of its advantages and is far less costly since a motor of fairly high voltage can be used, the current being correspondingly low; on this system the motor-generator has only to develop a small voltage at full load and less than the line voltage at light loads. Thus the output of the motor-generator is of lower power than that of the Ward–Leonard set, allowing a much higher speed and consequently smaller frame size to be used. This system is now largely used for windlasses and capstans.

Briefly, the outfit consists of the main windlass or capstan motor supplied with current from the ship's auxiliary supply, and in series with the motor armature is the armature of the generator of a reversible booster set. The motor of the booster set obtains its supply direct from the ship's auxiliary supply. The main motor can therefore be supplied with a voltage which can be controlled from zero to almost double the line voltage. By this means very fine control of the main motor can be obtained, and the whole arrangement is as nearly foolproof as is possible of attainment.

Cargo Winches.

In view of the importance of these auxiliaries (any trouble with the winch equipment may result in delay in unloading, with consequent deterioration of the cargo, and added expense on account of the ship itself being held up), it is essential that the electrical equipment associated with them should be of the most robust character. The design should permit of easy and reliable control in the hands of unskilled operators.

Well-designed contactor gear fulfils these requirements, and its use is strongly advocated for cargo-winch working. The equipment consists of electrically operated contactors working in conjunction with a master controller; a reliable form of time-delay device should be employed for controlling the acceleration of the contactors. Magnetic brakes of the disc or solenoid type, worked in conjunction with mechanically operated hand or foot brakes, are generally used to control the load whilst it is suspended. Dynamic braking has also been used with satisfactory results. Booster-controlled winches have given good service, but this form of control does not appear to have been used so extensively for winches as for windlass and capstan working, probably on account of expense.

It is suggested that wherever possible the electrical equipment of deck auxiliaries should be housed below deck or in deck houses. The greater efficiency of working in the latter case, due to the protection afforded the operator, will more than repay the extra cost involved; whilst in the case of capstans and windlasses there may be a great saving as ventilated gear may be used, with improvement in reliability owing to better overhaul facilities. In cases where it is impossible to protect the equipment it is necessary that it should be absolutely watertight and that its mechanical design should be of the most liberal nature. Even when the best of designs is employed, rapidly varying temperatures introduce the risk of condensation inside the machines and controllers, and breathing must be provided for.

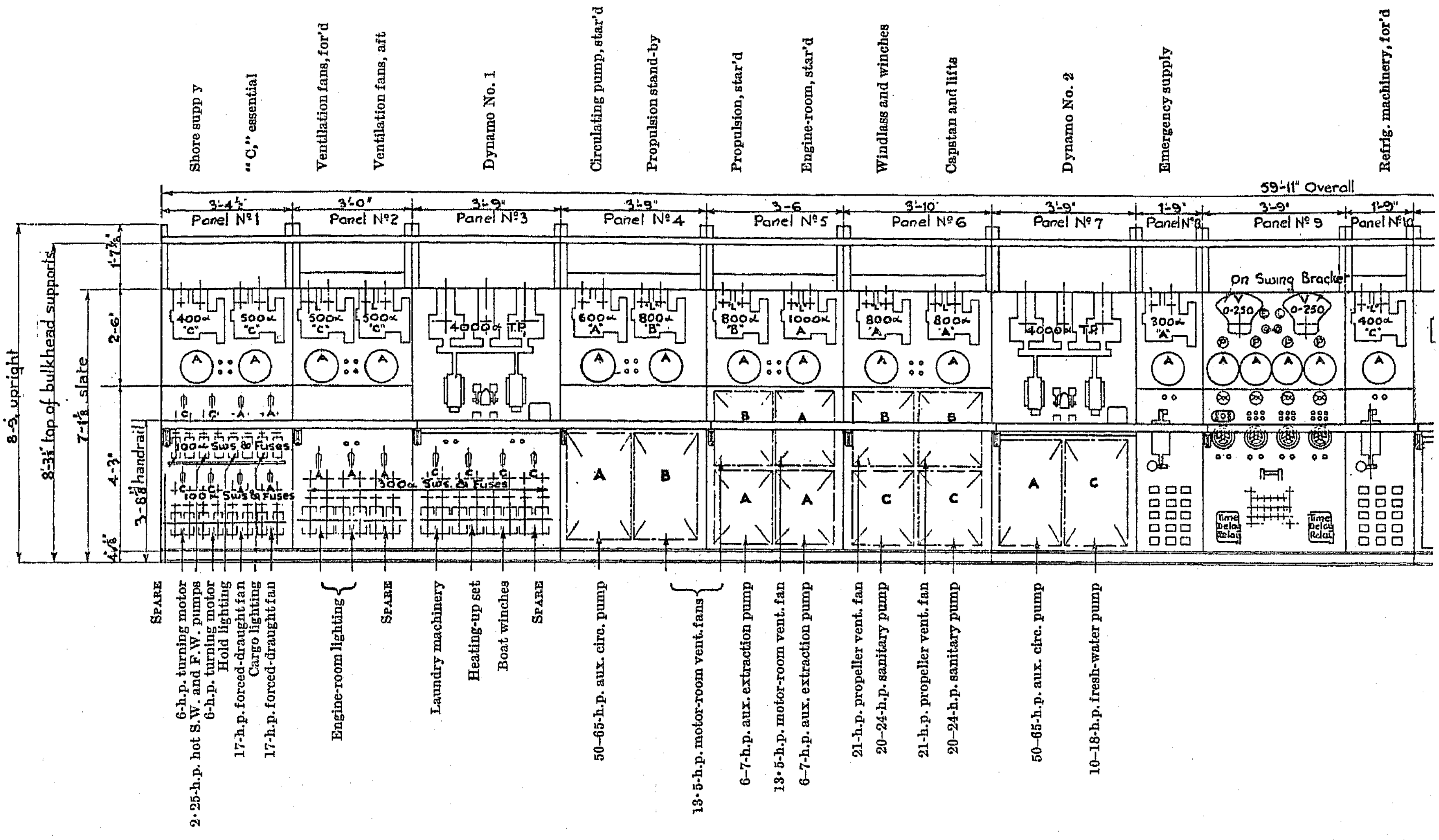

FIG. 1.—Outline arrangement of main switchboard (220 volts, direct current).

Circuit marked " L " denotes links for ring mains. Letters "A," "B," or "C," indicate category of essential tripping to which circuit is connected.

It will be appreciated from the foregoing remarks that the insulation of deck machinery needs the most careful consideration. Mica or micanite are, in the authors' opinion, the best materials for this duty.

MOTOR STARTERS AND CONTROLLERS.

The importance of simplicity and reliability in the control of marine electrical equipment has for many years engaged the attention of electrical engineers. It is essential that at all times the operator should be relieved of anxiety as to the rate of acceleration when starting motors, and that misuse of the starter and the motor should be impossible. It is frequently desirable that a particular motor or group of motors shall be capable of being started up, or having its speed controlled from a remote or centralized position, and that indication shall be given that the machine is working satisfactorily.

For instance, it should be possible at all times for a spare steering-gear motor to be instantly started up from the bridge, or on a failure of the supply to the main busbars the emergency steering-gear motor should immediately come into operation automatically from the battery. A forced-draught fan, situated in a house on the boat deck, should have facilities for being started up and stopped from a position adjacent to the machine itself (to enable the engineer to ascertain that it is running properly), while starting and stopping and the speed should be controlled as required from the floor of the boiler room. These requirements have led to the increasing use of automatic starters, and their use is advocated on every possible occasion. It is necessary that the time-delay device should be robust, reliable, and easily understood by the engineers responsible for its maintenance, so that repairs or replacements can be readily effected if necessary.

Many ingenious forms of time-delays have been developed, some operated by current control, others by the back e.m.f. of the motor itself, and yet others by mechanical means. While the first two types are largely used with satisfactory results they suffer from the disadvantage (particularly where remote control is used) that should the machine fail to complete its starting sequence the starter may remain in circuit, with resultant damage to the starting resistance and to the starter itself. Another disadvantage of some of these types is that when reciprocating machinery such as compressors, where the starting peaks fluctuate violently, is being started, there is a danger of the starter completing its sequence before the motor is up to speed. Air and oil dashpots are not recommended for marine use, as owing to variations in temperature between the tropics and colder zones they cannot be relied on to give a definite time-delay under all conditions.

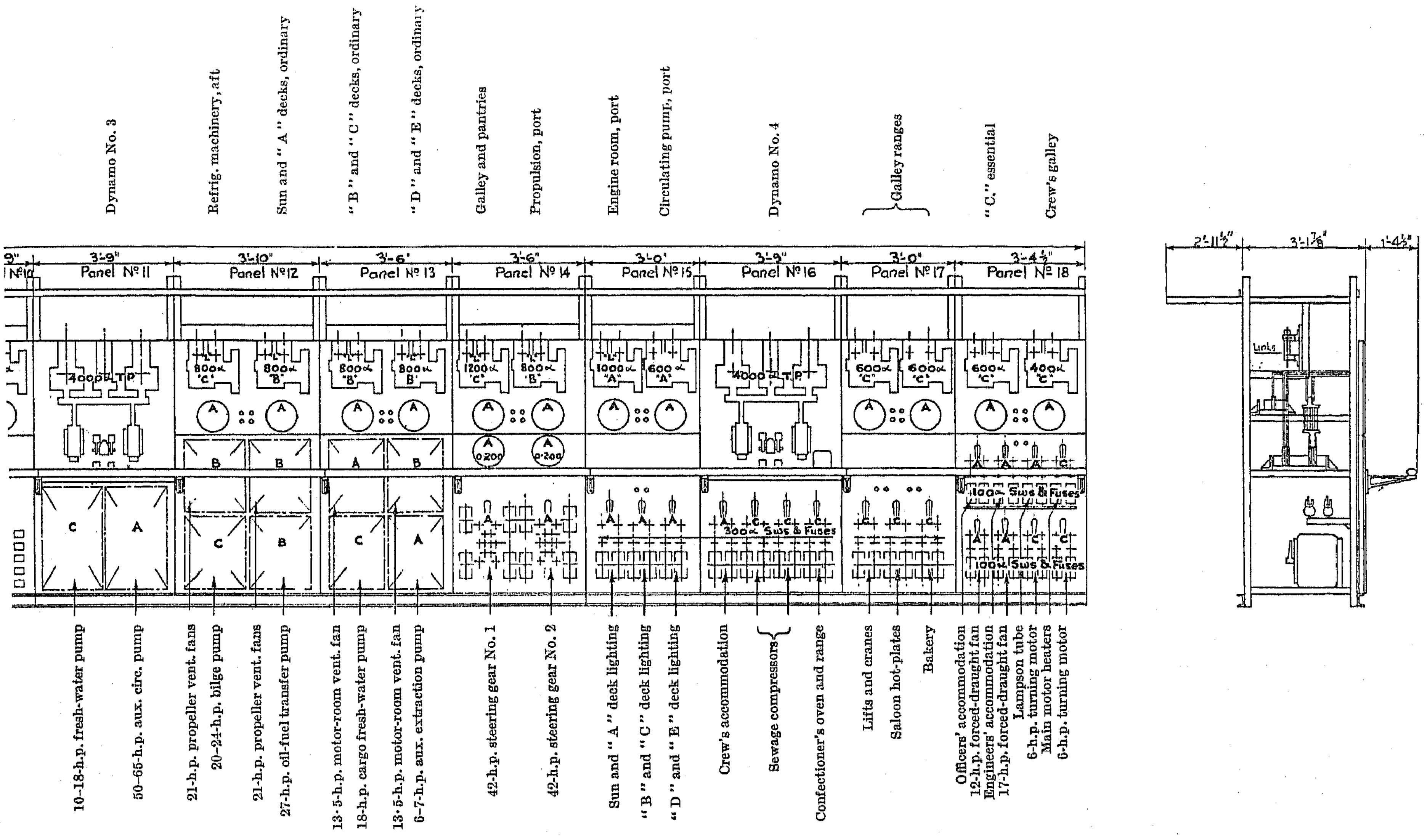

FIG. 1 (*continued*).

Timing starters equipped with a clockwork timing device will accelerate a motor at a predetermined rate irrespective of load. The rate of acceleration is adjustable within a wide range according to the size of the motor. Should trouble such as a seized bearing or a jammed pump occur, the starter will progressively cut out the starting resistance until tripped by the overload relay, without damage to any of the equipment.

Automatic starters can be arranged for local and for remote control by means of push buttons, float switches, or pressure switches.

Limitations of space, particularly in engine rooms, have led to the development of a particularly interesting type of starter whereby one starter is made to serve a group of motors. The advantages of this type of starter, particularly for large engine rooms, will become apparent when consideration is given to the fact that a large number of auxiliaries are started up and run continuously throughout the voyage. In consequence the starter operates for a few seconds and then occupies valuable space, often for several weeks, without being used.

In one system which has been installed in a number of large ships a group starting means known as a "plural starter" (Fig. 3) is used for all engine-room motors and refrigerating machines within a range of 5 h.p. to 50 h.p. approximately. Two starters and starting resistances are fitted at the back of the main switchboard and are coupled to a 2-way change-over switch. By means of this switch either starter can be instantly brought into use, and there is therefore a spare starter available for all machines at any time.

The starter consists of a motor-driven multi-contact drum controller, the driving motor being compound wound and having a separately excited field winding connected across part of the starting resistance. Consequently, with a heavy starting current there is a correspondingly heavy current through the field winding, and the speed of the controller motor is reduced. This results in a slow starting rate for a large machine and a more rapid rate of starting for a smaller machine.

Each machine on the plural starter has associated with it a contactor panel, and all these contactor panels are grouped together at the main switchboard. The active portion of the equipment is thus under the supervision of the switchboard electrician and is easily accessible for cleaning and maintenance.

Each contactor panel is equipped with positive and negative line contactors and a starting contactor, together with an adjustable overload relay. Mounted on each of the motors, in place of the usual terminal box, is a motor starting unit in a steel case with a door and inspection window, containing start and stop push-buttons, pilot running-light, and an ammeter. In the case of a variable-speed machine a shunt regulator with full field starting interlock is also provided.

Another form of control of this type, known as the "Uni-start" system, employs for the smaller motors a starter of the solenoid type, and the timing device consists of an eddy-current disc working between the poles of an electromagnet excited by the load current. For starting the larger motors a contactor-type starter is used, the individual contactors which progressively cut out the starting resistance being controlled by an eddy-current timing device similar to that employed for starting the smaller machines.

MOTOR DESIGN.

There are certain drives, such as for deck machinery, forced-draught fans, etc., for which the use of totally enclosed or pipe-ventilated machines is preferable or at times essential. With the exception of these instances, enclosed ventilated machines, protected against dripping moisture, have proved quite satisfactory. In order to ensure continuous reliability, however, it is necessary that the motors should have large openings with easily removable covers to permit of ready inspection of the machine and easy accessibility for cleaning purposes. It is also necessary that the operating personnel should make use of these facilities, as in the authors' experience a very large proportion of such electrical troubles as have occurred with motors and generators owe their origin to the presence of accumulated dirt and oil.

Ball and roller bearings are being used in increasing numbers and their use is advocated wherever possible, provided the design of the housing is sufficiently accessible to permit of easy inspection and removal. The housing should also be sufficiently robust in construction to prevent distortion, and it must be capable of efficiently retaining the grease. Self-aligning bearings if well designed tend to eliminate much of the trouble which can be experienced due to errors of assembly and alignment.

There are certain machines such as ventilating units and others, situated in close proximity to the bridge or to passenger accommodation, for which the maximum attainable degree of silence is essential. Noises may originate from two sources, mechanical and magnetic.

The main causes of mechanical noises are (1) bearings, (2) windage, and (3) brush chatter. Journal bearings are undoubtedly quieter in service than roller or ball bearings and it is desirable to use journal bearings where a special degree of silence is necessary. Well-designed ventilating ducts and fans will eliminate as nearly as practicable noises due to windage, and provided the brush gear is of robust construction and the commutator maintained in reasonable condition no trouble should arise through brush noises.

In d.c. machines, noise of magnetic origin is usually most troublesome as the noise is often of a penetrating nature and may vary in pitch and degree with any change in load or speed of the machine. It is not proposed to enter into details regarding the design of super-silent machines, beyond referring to the fact that the chief source of magnetic hum is variation of flux density in the air-gap due to changing reluctance in the magnetic circuit as the armature teeth pass under the poles. Noise due to this cause can be reduced to a minimum if the armature slots are skewed relatively to the axis of the shaft, or alternatively by skewing the poles or pole shoes. Carefully-chamfered pole-shoes also help to reduce noise by minimizing any disturbance caused by the teeth entering or leaving the pole face.

From the foregoing it will be seen that ordinary commercial standards of silence are not suitable in the case of machines in proximity to the bridge or to passenger accommodation. Super-silent machines should always be specified for these duties.

HOTEL LOAD.

A modern liner is really a large floating hotel, and when at sea the travelling public demand a standard of comfort as high as or even higher than that obtaining in the best hotels ashore. The shipowner, therefore, in his effort to attract the travelling public to his ship, has con-

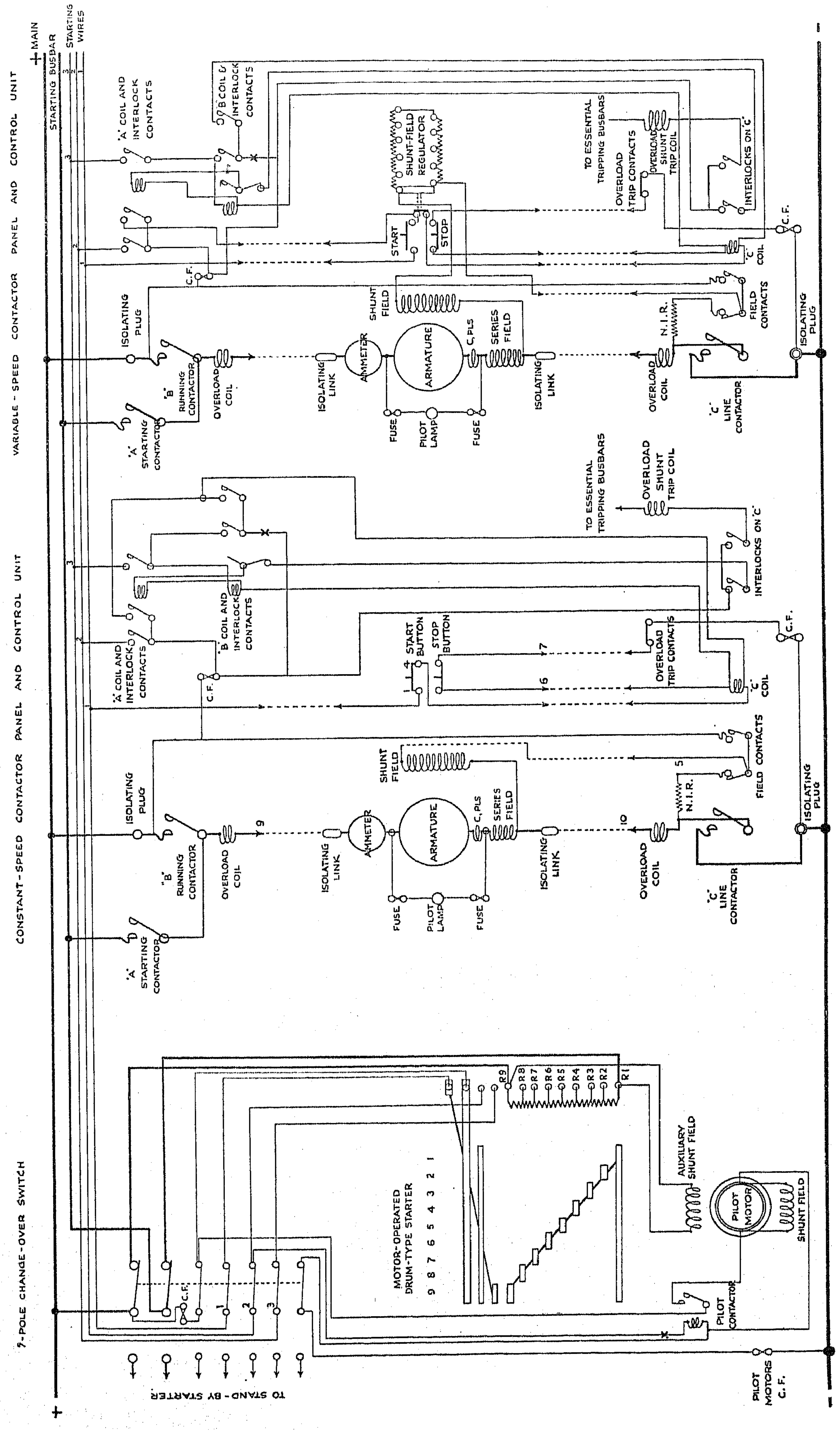

FIG. 3.—Schematic diagram of connections for plural starting equipment.

centrated upon electricity to provide every known means of comfort and safety. Consequently the most modern types of lighting, heating, and cooking, equipment are installed. Telephones and lifts are provided for every possible occasion, and illuminated signs and signalling systems have been developed which are the last word in efficiency.

Apart from questions of safety and speed, a ship's reputation may be made or marred by the quality of its cuisine, and electricity offers unrivalled facilities in this sphere.

The magnitude of a modern galley installation will be made manifest when it is pointed out that the maximum galley load may be between 600 and 700 kW.

CABLES.

The importance of the cables on a ship cannot be stressed too much: the cables are the only link about which there may be doubts as to whether it will stand up to the demands made during the 25 years' service which is expected of the ship and of all the gear in it.

There has been considerable difference of opinion regarding the use of pure rubber next to the copper strand. In this connection, the Admiralty has had considerable experience from which the merchant service would be wise to benefit. Single-conductor cable should be avoided, and 3/·029 in. should be the smallest size used. This ensures greater flexibility than would be the case if an equivalent single conductor were used, and the cable is less liable to fracture when bending.

Lead-covered cables should be braided in order to protect the lead when the cable is being pulled through bulkheads, etc., and all cables should be fire-resisting compounded overall as a precaution against the spreading of fire along the braiding. This protection may take the form of a white-lead compounding. Where subject to mechanical damage the cable should be armoured and again braided and fire-resisting compounded.

There is no doubt that the question of cable-runs in a ship should be given more and earlier consideration than has been devoted to it in the past. It is becoming recognized that, with the increasing use of electricity on board ship, particularly for propulsion, the lay-out of the cable-runs needs even more care than that of the pipe-runs. The latter, especially in a passenger vessel, present a big problem, and the cable-runs are often even more complicated. If correct and just consideration is given to these points, and if the best of cables are used, ship-owners can rest assured that the life of their cables will equal the life of the ship.

MISCELLANEOUS EQUIPMENT.

There is probably no more concentrated application of electricity than in a passenger liner of, say, the following dimensions: 550 ft. long, 75 ft. beam, 100 ft. (approx.) depth. The following is a list of equipment, apart from machinery, installed in the "Queen of Bermuda," a modern liner of approximately the above dimensions and carrying 800 passengers.

Galley Equipment.—This includes 2 8-oven island ranges; 20 hot cupboards; 1 fish fryer; 2 baking ovens; salamanders, hot-plates, and carving tables; 10 electric water boilers and urns.

Miscellaneous.—1 450-line telephone board; 250 electric signs and indicators; 2 250 bell pushes; 400 electric radiators; 400 electric towel rails; 650 electric fans for cabins; 410 miles of conductors in cables and wires; 5 000 fuse units; 6 000 switches and control units; 5 000 lighting fittings; 20 000 electric lamps.

It is interesting to note that the efforts that have been made towards standardization of accessories in recent years have been so successful that 80 different patterns will cover the whole of the lighting fittings for cabins, all utility deck fittings, fuses, fans, switches, plugs and sockets, lampholders, heaters, bells, fire alarms, and telephones. The design of each of these fittings has to be studied from the point of view of corrosion, water-tightness, and rough usage, and each one of them presents a special problem when compared with the standards that are used for shore working. In very few cases are the accessories normally used ashore suitable for shipboard use.

Part 3. ELECTRIC PROPULSION.

CHOICE OF SYSTEM.

Present-day practice has resolved the variety of schemes which have been put forward for electric ship propulsion during the past 25 years into two classes, namely (1) turbo-alternators with synchronous motors, for large ships; and (2) Diesel engines with d.c. generators and motors, for small ships. The line of demarcation between these two categories is not very clear. The maximum horse-power permissible with direct current is limited by the current to be carried by the commutators, control gear, and cables.

On the other hand, at this limit, the maximum economical limit of the Diesel engines has not been reached. An attempt to bridge over the gap between the two methods is the suggestion to use Diesel engines with a.c. generators, and synchronous motors. This has not yet been put into practice, but may have possibilities in the future.

TURBO-ELECTRIC DRIVE.

For very large ships there is little doubt that the turbo-electric drive is the most suitable at present. With this scheme, the a.c. generators are direct-coupled to turbines and supply 3-phase current to synchronous propulsion motors.

The frequency at normal speed has been usually fixed at 50 cycles per sec. for ships built in this country, probably because it is the standardized frequency for land practice. Actually there is no reason why the frequency should not be chosen at any value, having regard to the speed of the turbines and alternators and to the windings of the alternators and motors. In the French ship "Normandie," the frequency will be 81 cycles per sec., the alternators running at 2 430 r.p.m.

Turbo-Alternator Design.

The electrical design of the alternators is little different from that common in land practice (see Plate 1, Fig. 4), the chief point being that all insulation must be of special quality for use in a damp salt-laden atmosphere with larger variations in temperature. The mechanical design of the turbine and alternator rotors, however, presents points of interest, since there must be no critical speed below the normal speed of rotation. Care must also be taken of the stresses occasioned by rapid deceleration when reversing the propellers.

The alternator is usually ventilated by means of a closed air-circuit, the air being cooled by sea water. Heaters are placed in the air-circuit to avoid extreme variations in temperature when the machine is standing.

Since there is no relation between the positions of the turbine shaft and the propeller shaft, as there is in a geared turbine drive, a very compact lay-out is possible. The condenser is placed immediately below the turbine, and the cooler below the alternator.

The relative merits of the induction motor and the synchronous motor for ship propulsion have frequently been discussed elsewhere. The principal reason for the choice of the synchronous motor lies in the higher power factor, which reduces the size of the alternator, cables, and switchgear.

Motor Design.

The electrical design of the motors (Fig. 5) again follows land practice, except for the insulation. Care must be taken in the design of the pole-face damping winding which is used for starting and reversing. This winding is not so efficient as a complete squirrel cage owing to the interpolar gaps, but it can be designed to give sufficient torque for rapid reversals.

Ventilation of the motors is effected by separate motor-driven fans through a closed circuit, or the air may be passed through coolers back into the motor room. Heaters are placed in the air-circuit to avoid extreme variations of temperature when the machines are standing.

The mechanical design of the motors is characterized by the fact that every part must be as rigid as possible and yet no weight must be wasted. Considerable ingenuity has to be exercised to fit the motors into the space available, having regard to accessibility for inspection and repair. The lubrication of the bearings has to be fully effective down to very low speeds. This problem has been solved by the use of disc and scraper lubrication (see Plate 2, Fig. 6).

In twin-screw ships, two alternators are provided, and for full speed each alternator supplies current to one motor. For cruising speeds it can easily be arranged that both motors are supplied from one alternator, with a consequent increase in efficiency.

Operation.

In a twin-screw ship, when running normally with two alternators and two motors, there is no question of the alternators or motors being overloaded except when the ship is being turned. Under the condition of full helm the alternator and motor on the inboard side of the circle tend to take more load, but they are prevented from doing so since the steam admission is limited to that required for full load. The alternator and motor on the outboard side of the circle will take a reduced load. When, however, both motors are driven from one alternator, they are capable of absorbing twice the power of the alternator. A speed-limiter is therefore automatically brought into operation which alters the governor setting so that the speed cannot rise above 70 per cent.

In quadruple-screw ships, four alternators can be used, but in the "Monarch of Bermuda" and the "Queen of Bermuda" only two were installed, four screws being used—probably for reasons of shallow draught in ports where these ships have to trade. This arrangement of machinery might be found the most suitable for other vessels where the power is within the capacity of two alternators, because if only two motors were used their dimensions, as well as the size of shafting and propellers, might be found excessive. By a comparatively simple system of switching (Fig. 7) it is possible to obtain the following methods of connection:—

(A) Two port motors to port alternator, two starboard motors to starboard alternator.

(B) Two inner motors to port alternator, two outer motors to starboard alternator.

(C) Two inner motors to starboard alternator, two outer motors to port alternator.

(D) Inner port motor to port alternator, inner starboard motor to starboard alternator.

(E) Outer port motor to port alternator, outer starboard motor to starboard alternator.

(F) All four motors to port alternator.

(G) All four motors to starboard alternator.

Under condition (A) the two motors on the port side must run at the same speed, and similarly for the starboard motors.

It was anticipated that the load taken by the inner propellers would be different from that taken by the outer ones. Conditions (B) and (C) were therefore arranged so that the inners could be run at different speeds from the outers and the load equalized. The amount of difference in r.p.m. required depends, no doubt, on the stern tube bossings, the spacing of the propellers, the lines of the ship, and the angle of the "A" brackets.

Two protective devices are required to prevent overload on the machines under some of the conditions. For conditions (D) and (E), the turbine speed must not be brought up to full value, as otherwise the motors would be overloaded. Since only half the motors are in use, the speed can only be about 70 per cent to give half torque to the propellers. A speed-limiter is therefore automatically brought into operation, which alters the governor setting so that the speed cannot rise above 70 per cent. The motors are then fully loaded in current, since they are each producing 100 per cent torque. The horse-power of each motor, however, is 70 per cent of its normal output (since the speed is 70 per cent), and the output of each alternator is only 35 per cent of normal. In addition to the speed-limiter, therefore, a load-limiter is also introduced to limit the maximum flow of steam so that the turbine cannot develop more than 35 per cent of its normal output at 70 per cent speed. This is necessary to prevent overloads on the alternators and motors when turning.

For conditions (F) and (G), the speed must again be limited to 70 per cent, but the load-limiter is not re-

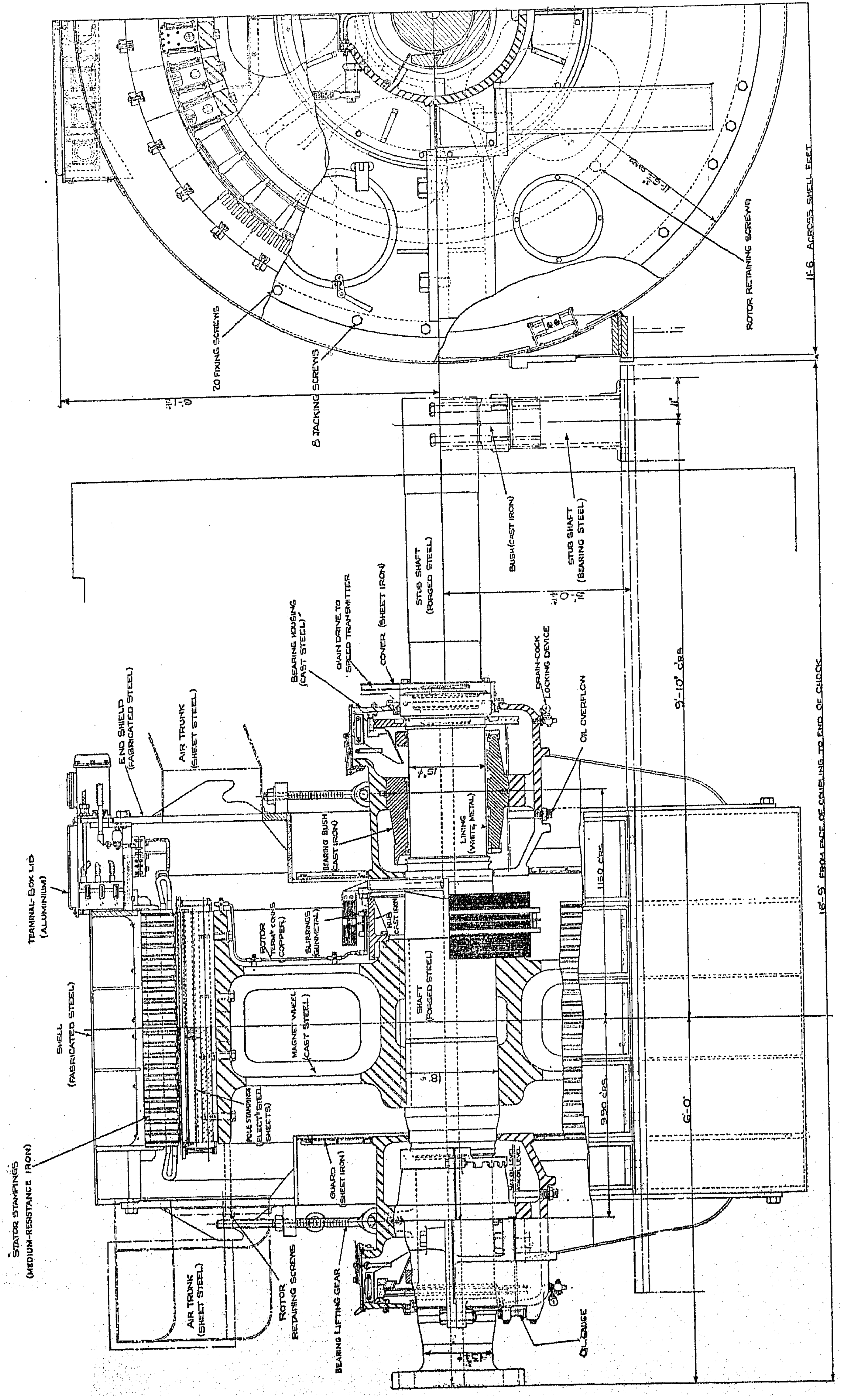

FIG. 5.—Sectional arrangement of 3 000-volt 5 000-s.h.p. ship propulsion motor.

quired. The output of the alternator is 70 per cent of normal at 70 per cent speed.

For normal running, the steam is limited so that an overload cannot be put on the alternators. If an overload tends to arise on one side of the ship, due to turning, the turbine slows down so that normal load is not exceeded. With a twin-screw ship, this means that neither the alternator nor the motor is overloaded. With a quadruple-screw ship, when one alternator supplies two motors, the total load on the two motors is limited, but not the individual load on each motor. The amount of overloading, however, is not serious, as will be seen by the following readings taken during the circling trials of the "Monarch of Bermuda."

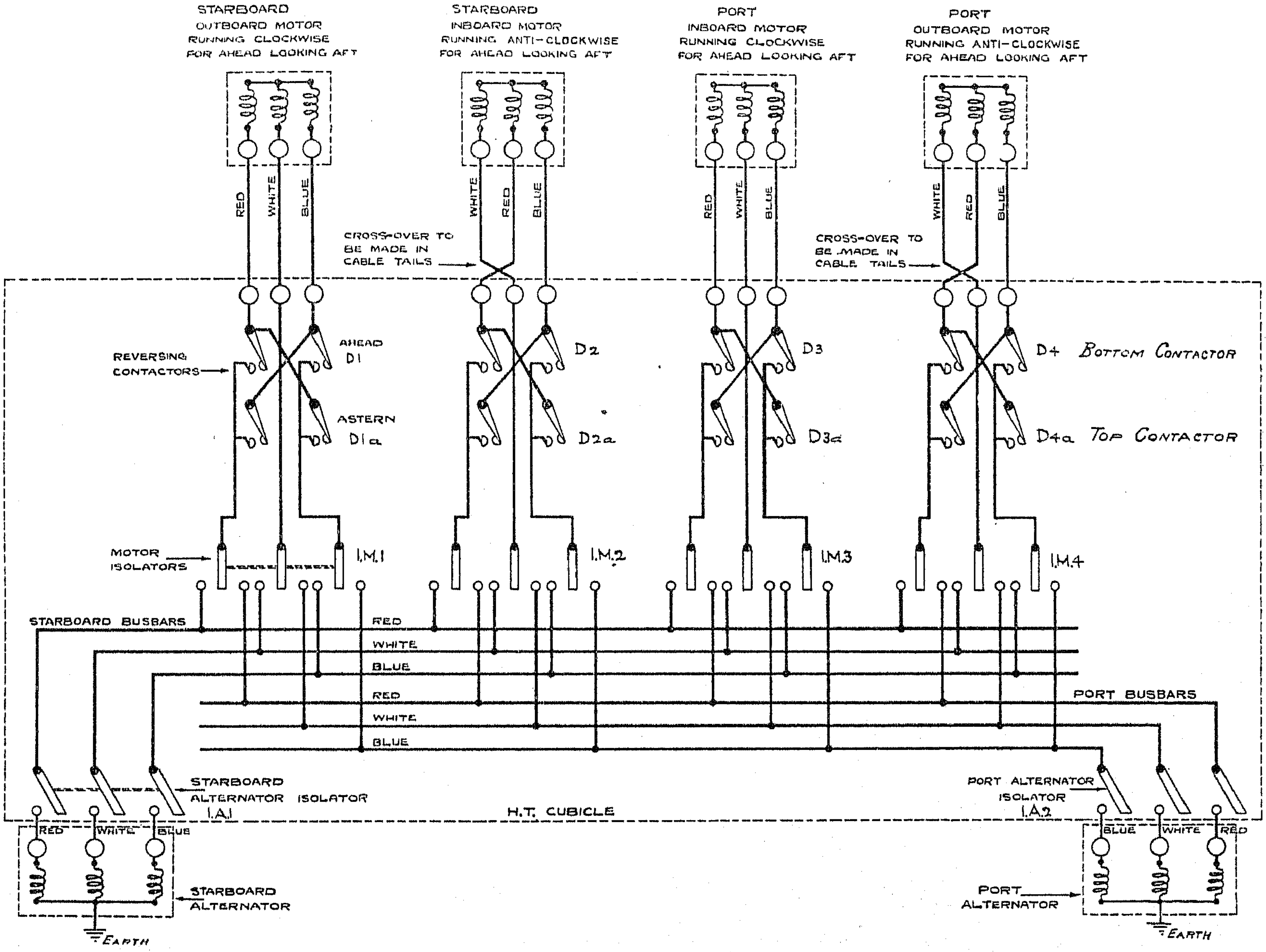
STARBOARD OUTBOARD MOTOR RUNNING CLOCKWISE FOR AHEAD LOOKING AFT
STARBOARD INBOARD MOTOR RUNNING ANTI-CLOCKWISE FOR AHEAD LOOKING AFT
PORT INBOARD MOTOR RUNNING CLOCKWISE FOR AHEAD LOOKING AFT
PORT OUTBOARD MOTOR RUNNING ANTI-CLOCKWISE FOR AHEAD LOOKING AFT
RED
WHITE
BLUE
CROSS-OVER TO BE MADE IN CABLE TAILS
REVERSING CONTACTORS
AHEAD D1
ASTERN D1a
D2
D2a
D3
D3a
D4 Bottom Contactor
D4a Top Contactor
MOTOR ISOLATORS
I.M.1
I.M.2
I.M.3
I.M.4
STARBOARD BUSBARS
PORT BUSBARS
STARBOARD ALTERNATOR ISOLATOR I.A.1
H.T. CUBICLE
PORT ALTERNATOR ISOLATOR I.A.2
STARBOARD ALTERNATOR
PORT ALTERNATOR
EARTH
EARTH

FIG. 7.—Diagram of 3-phase stator circuits for the electric propulsion equipment of the turbo-electric vessel "Monarch of Bermuda."

D1 and D1a = Starboard outboard motor direction contactor.
D2 and D2a = Starboard inboard motor direction contactor.
D3 and D3a = Port inboard motor direction contactor.
D4 and D4a = Port outboard motor direction contactor.

I.M.1 = starboard outboard motor isolator.
I.M.2 = starboard inboard motor isolator.
I.M.3 = port inboard motor isolator.
I.M.4 = port outboard motor isolator.

(*a*) Two port motors to port alternator, two starboard motors to starboard alternator: port outer, 32 per cent of total s.h.p.; port inner, 16·5 per cent of total s.h.p.; starboard inner, 28·5 per cent of total s.h.p.; starboard outer, 23 per cent of total s.h.p.

(*b*) Two inners to port alternator, two outers to starboard alternator: port outer, 27 per cent of total s.h.p.; port inner, 17 per cent of total s.h.p.; starboard inner, 34 per cent of total s.h.p.; starboard outer, 22 per cent of total s.h.p.

In both cases the ship was turning to starboard.

Control Gear.

Since turbo-electric propulsion finds its best application in the case of large vessels, it is evident that high-voltage systems have to be adopted in order to keep the current down to minimum values, so as to limit the size of cables and switchgear. This in turn demands additional precautions, in order to safeguard the personnel, and the h.t. control gear must be of a mistake-proof nature.

It is the practice, therefore, to install all selector switches, direction switches, and connections, inside steel-plate cubicles to which access can only be obtained when everything is dead. Moreover, when possible this gear should be arranged in a manner which will permit safely the cleaning and inspection of portions only of the h.t. apparatus whilst carrying on with the propulsion power available by means of the remainder.

For multiple-screw vessels, therefore, the control gear for each individual motor should be sectionalized in independent cubicles with suitable interlocks which permit of rapid isolation of any one motor and its control gear, whilst all other machines are left in commission. Furthermore, the control gear should be arranged in such a manner that rapid changes can be made in the running combinations of machines. For example, the " Monarch of Bermuda " and " Queen of Bermuda " are each fitted with four propellers each with its own motor, and operated normally from two alternators. The selector arrangements enable one man to change over this combination of machines within about ½ minute to any other combination, and to have the propellers running again at their maximum speed, without passengers on board realizing that there has been any stoppage whatever.

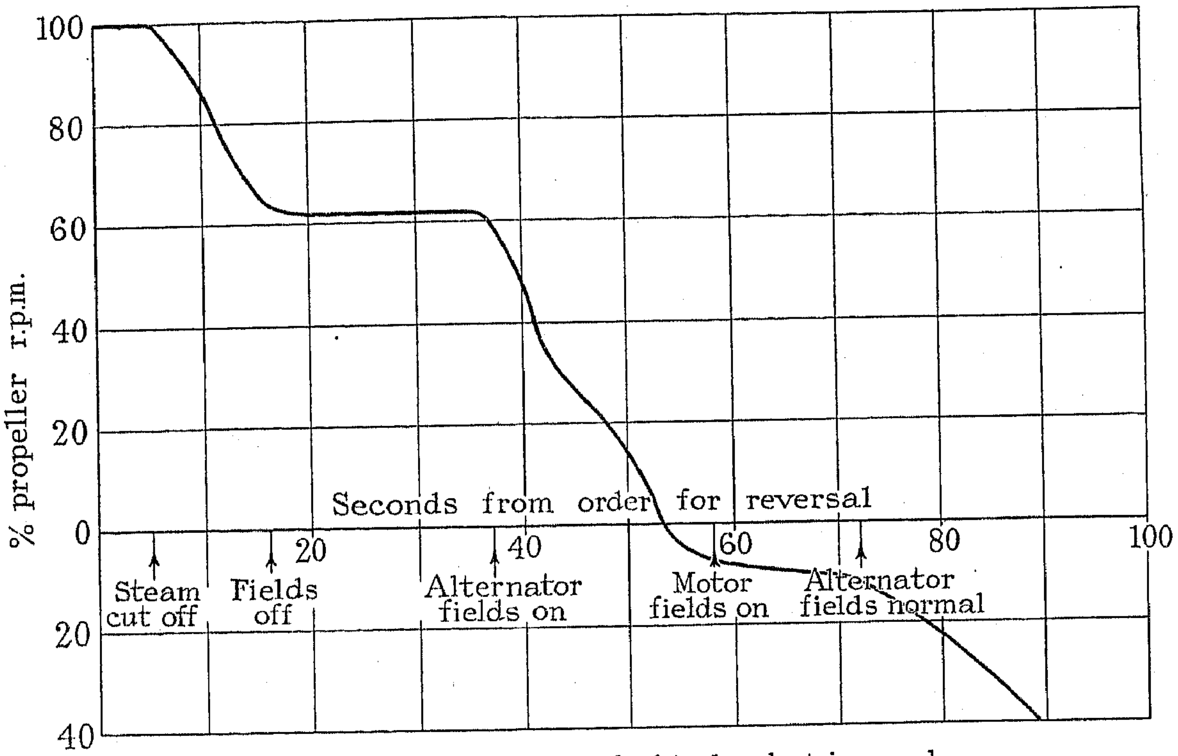

FIG. 9.—Full-speed reversal of turbo-electric vessel.

The scheme of control for a.c. drive using synchronous motors is briefly as follows. Speed control is obtained by varying the frequency of supply, i.e. by varying the speed of the turbine driving the generator. This can be readily carried out by means of levers or wheels on the control board through the medium of oil relay systems or servo motors, which alter the governor setting of the turbine.

Since large starting and reversing torque is required for quickly accelerating and stopping the propellers and the vessel, the motors are usually started as salient-pole induction motors, afterwards synchronized at low speeds, and then adjusted to whatever running speed is required. The control gear is arranged at a central position in the engine room, and takes the form of handwheels or levers for each turbo-generator (see Plate 2, Fig. 8).

The following description of control gear refers to that used on the two " Bermuda " vessels. This constitutes the most comprehensive control gear afloat, or that is even possible, and yet it is absolutely reliable and flexible. The gear for a twin-screw vessel is correspondingly simpler. Since there are four motors any number of which may be connected to either one alternator, each motor is provided with its own reversing switches, which are electrically closed, latched in mechanically, and tripped electrically. Small handwheels are therefore provided for each motor which decide whether such motor should be put into service or not as required.

Since there is no advantage to be gained by reversing a port outer motor whilst leaving the port inner ahead, arrangements are made so that reversal of both motors in service on the port side can be made simultaneously, and similar arrangements are provided to reverse simultaneously both motors in service on the starboard side; but the reversal of the port side is quite independent of the reversal of the starboard side, whatever the combination of running of motors and alternators.

With the control wheel at " stop," all direction and field switches are open and the turbine governor set for about $\frac{1}{5}$ speed. Movement of the control wheel in a clockwise direction first causes the closing of the various direction switches of all motors associated at the time with that wheel, in the ahead or astern direction, according to the positions of the port and starboard direction wheels. Further movement of the wheel causes the alternator field contactor to close with double excitation. A sequence catch arrests motion at this point, and the operator pauses to allow the motors to run up as induction motors to their maximum speed at $\frac{1}{5}$ normal frequency. Since the voltage is also low, owing to the low speed, the starting-current peaks are kept down to a minimum value. Ammeters and revolution indicators show the response of the motor, and when they are nearly up to synchronism the operator passes through the sequence catch and closes the motor-field contactors to pull the motors into synchronism. A second sequence catch arrests motion again, and when the motors are synchronized, as shown on the indicating instruments, the operator passes through the second sequence catch and closes the field contactor of a negative booster set which reduces the alternator field to normal running value.

Up to this point the control wheel has made one complete revolution, and the switching operations have all been carried out at $\frac{1}{5}$ speed. The wheel can now be turned through a second complete revolution, which has effect only on the setting of the turbine governor, permitting this to be raised up to full speed. Fig. 9 indicates the variation in propeller speed which occurs during the full-speed reversal of a turbo-electric liner.

Reduction in speed is carried out by rotating the control wheel in an anti-clockwise direction, in which case there is no hold-up by the sequence catches. The first return revolution of the control wheel reduces the governor setting to $\frac{1}{5}$; the second revolution opens all the field contactors and energizes a 5-sec. time-delay, which in turn permits the direction switches to open only when the heavy induced current due to the breaking of the fields has died away. The direction switches may then if desired be reversed and the starting sequence repeated as described above.

An alternative direct mechanical control is provided for direction switches and field contactors, which is instantly available in the event of failure of the electrical closing operations, and this mechanical operating mechanism is fully interlocked to prevent mal-operation in service. Reference has already been made to the speed- and load-limiting features.

In the P. and O. liners "Viceroy of India," "Strathaird," and "Strathnaver," the scheme of control is on the same general principle, but all these vessels are twin-screw only, and the control is carried out by three levers for each side of the vessel. These levers are interlocked to prevent incorrect operation. One lever controls the direction of rotation, one lever closes the field contactors, and one lever controls the speed by operating on the governor setting. In these ships also the switching arrangements are electrically operated, but the levers also actuate a mechanical follow-up gear, which would close the contactors mechanically by the same movement if the electrical closing failed to function.

DIRECT-CURRENT DIESEL-ELECTRIC DRIVE.

Advantages.

Since success has attended the use of Diesel engines for driving the propellers directly, it is not to be wondered at that the attention of shipowners has been directed to Diesel-electric drive. The addition of the electrical transmission has enabled economical values to be selected for the speeds of the engines and the propellers. A further invaluable advantage is found in the fact that the engines run in one direction only at constant speed, and are not subjected to frequent starting and stopping when manœuvring is being carried out.

Disadvantages.

The limitation of output of d.c. Diesel-electric propulsion lies in the value of the current necessary, since very high voltages are not desirable. This current necessitates very large commutators and heavy switchgear and cables. It is also found that the number of engines required is sometimes excessive.

Control.

In regard to the method of control, the Diesel-electric is of course far superior to the direct Diesel drive. In the former the whole of the speed regulation of the propeller in both directions is effected by controlling the comparatively small currents in the fields of the generators or motors.

Ward–Leonard system.—Most of the ships already built with Diesel-electric drive are controlled on the Ward–Leonard principle. The motors are excited in one direction from a separate source of supply, and the generators are also separately excited, but a regulator varies the strength of their field from a maximum in one direction to a maximum in the other. For small twin-screw boats using two engines, it is sometimes necessary to run both motors from only one engine, in which case arrangements may be made to reverse the motor fields after reducing the generator voltage to zero. At starting a small excitation is applied to the generator, producing a small voltage which sends a current through the motor armature. Since the motor field is excited, a torque is exerted which turns the propeller. As the speed rises, the field of the generator is progressively strengthened until the desired speed is obtained. It will be seen that if the generator field is strengthened too quickly before the propeller speed has had time to rise, excessive currents may flow which may cause dangerous sparking at the commutators, and possibly overload the engines.

The two principal methods of control on the Ward–Leonard system are known as the "direct" and the "follow-up" methods.

Direct control.—With a cam-operated controller or a face-plate controller, the regulator in the generator field is directly operated from the bridge by means of mechanical drive, the controller taking the form of an ordinary ship's telegraph. The regulator has a comparatively small number of sections (eight or ten) in the case of the former, but a much larger number in the case of the latter type.

Follow-up control.—The follow-up method of control operates on the "Wheatstone bridge" principle. The telegraph on the navigating bridge moves an arm on a potentiometer regulator. When this arm is displaced from the position of the corresponding arm of another potentiometer mounted on the main regulator, a circuit is completed which starts a small motor driving the main regulator and keeps it running until the arm on the second potentiometer again corresponds to the arm on the bridge. The motor then stops. Thus the regulator in the generator field cannot possibly be operated too quickly, however rapidly the telegraph is moved.

Propeller-racing.—In the Ward–Leonard system, if the generators are shunt-wound or lightly compound-wound, there is no danger of the propellers racing in a heavy sea. If the load comes off a motor, its speed rises a small percentage until its back e.m.f. is equal to the voltage of the generator, and the current falls to practically zero.

Over-power and reverse-power.—Since the current flowing in the generator and motor armatures depends on the difference between the generator e.m.f. and the motor back-e.m.f., a small change in one of these e.m.f.'s makes a large change in the current. It is therefore necessary to see that the generator e.m.f. is not altered so quickly that the motor back-e.m.f. cannot follow. In small vessels it has been found that the propeller speed can change so rapidly that very little over-power is produced when the telegraph is suddenly thrown from "stop" to "full ahead," and very little reverse power when it is thrown from "full ahead" to "full astern."

In order to avoid the necessity of providing the engines with a large margin of power, some form of over-power relay may be fitted which inserts a resistance in the generator fields if the power taken exceeds the normal power of the engines. In this way a heavy current may be taken at starting, when the voltage is low, but the current is limited when the voltage has risen.

Constant-current systems (described later) automatically take care of this question of overloading to a certain extent.

An alternative system which definitely prevents overloading during turning is called the "constant power" system (curve *b*, Fig. 10). This system consists of a separately-excited generator with a heavy counter-compound winding which has a drooping characteristic and can be so designed that the power supplied (volts × amps.) is approximately constant over a small range, and is equal to the engine power. Thus an overload due to turning the ship is prevented by the fact that as the voltage falls the current rises. A disadvantage of this generator is that the open-circuit voltage is rather high, so that there is a tendency towards propeller-racing in rough seas. This can be overcome by means of a voltage relay which inserts resistance in the generator field if the voltage exceeds a predetermined value.

For large vessels it may be found advisable to adopt the use of motor-driven field regulators, adjusted to operate over their whole range from "full ahead" to "full astern" as rapidly as possible, and to provide over-power and reverse-power relays (which can readily be combined in the same relay). Reverse power up to the value which will absorb the friction and driving losses of the Diesel engine is permissible, but any further power would tend to speed up the engine and must be prevented.

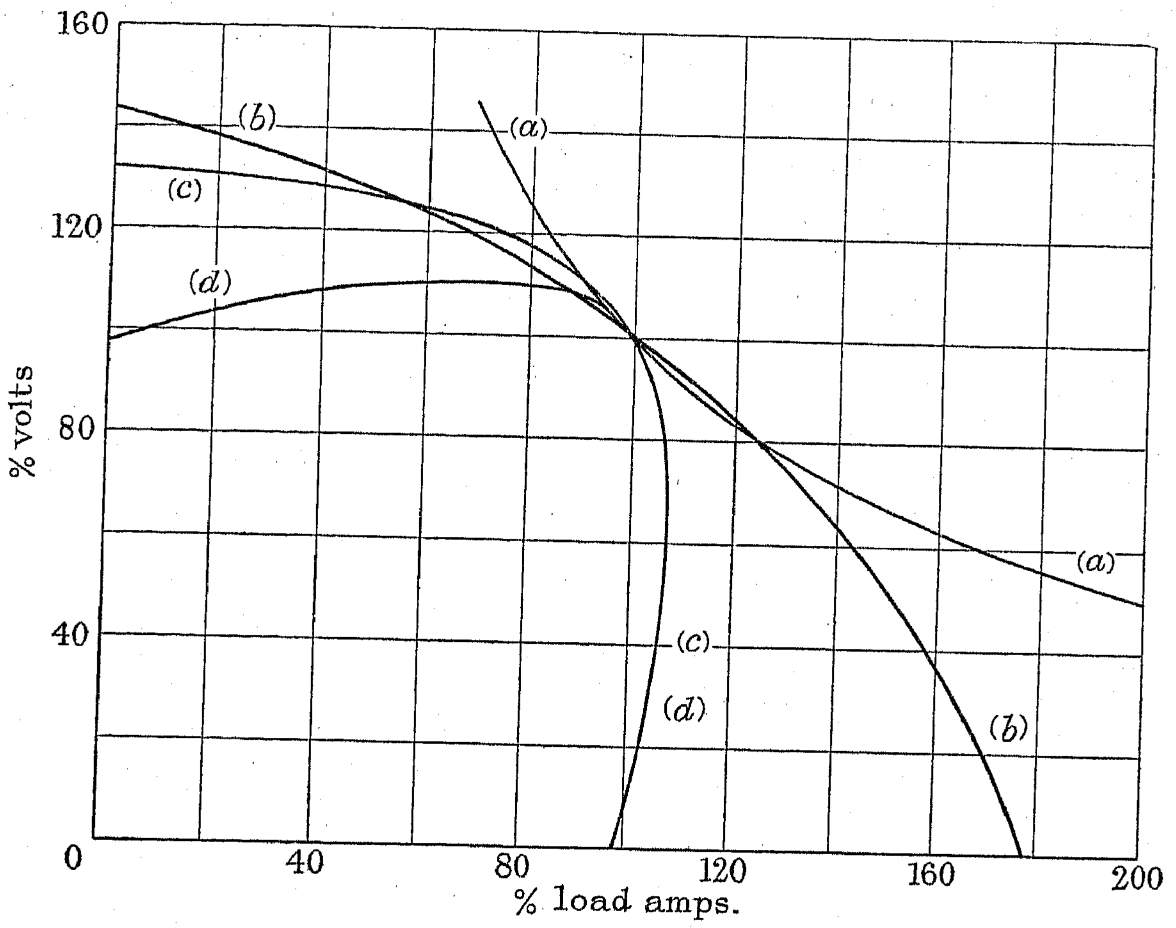

Fig. 10.—Generator characteristics for Diesel-electric propulsion.

(*a*) Theoretical characteristic for constant engine power.
(*b*) Constant-power system.
(*c*) Constant-current system.
(*d*) Austin system.

The reverse-power relay is arranged, therefore, to open the circuit of the motor driving the regulator, and prevent further reduction of forward voltage, or further increase of reverse voltage, until the vessel has lost sufficient way to reduce the value of reverse-power feed. The over-power relay can be similarly arranged to hold up the motor-driven regulator or alternatively to insert additional resistance in the generator field, thus reducing the voltage and consequently the speed, and therefore the load taken by the propulsion motor. By adjusting the values of relay settings, etc., slowing-down of the Diesel engines due to overload can be definitely prevented.

Switching.

Single-screw.—In a single-screw ship it is usual to use more than one engine and generator, as a safeguard

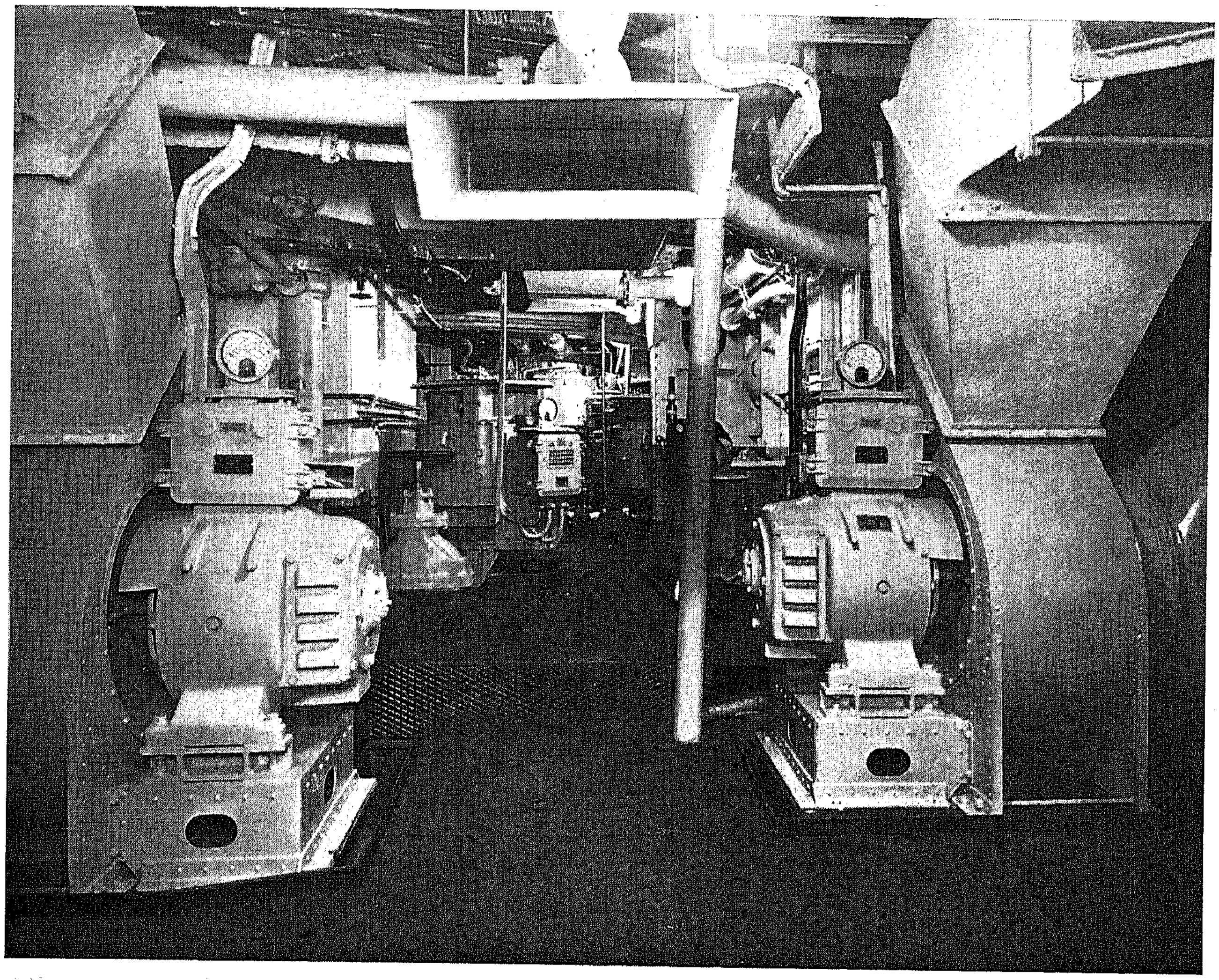

Fig. 2.—Motors with plural-starter control units driving engine-room auxiliaries. In foreground, ventilating fans for two propelling motors; in background, vertical-spindle pump motors.

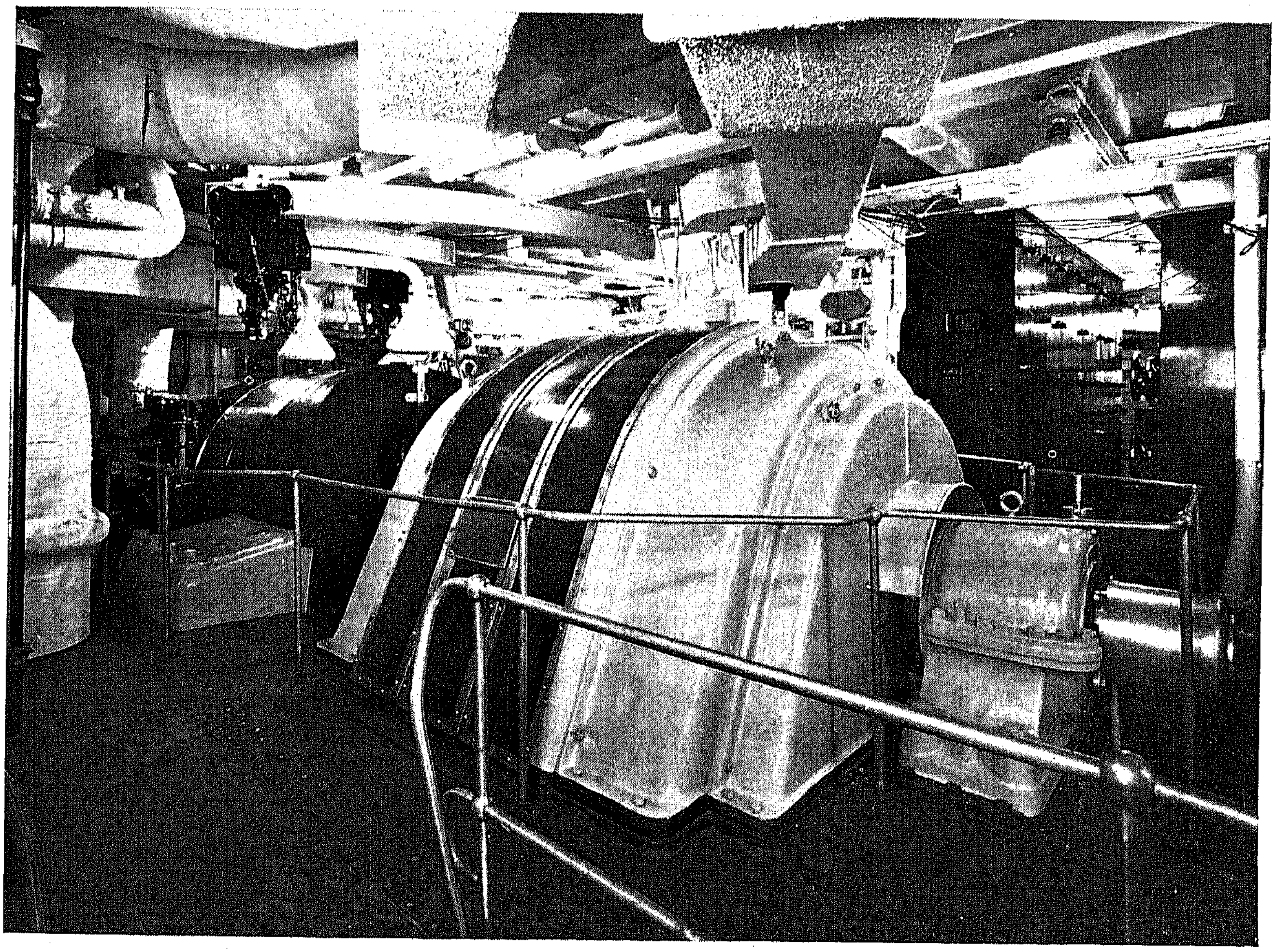

Fig. 4.—A 7 500-kW 3 000-volt 3-phase turbo-alternator installed in the "Queen of Bermuda."

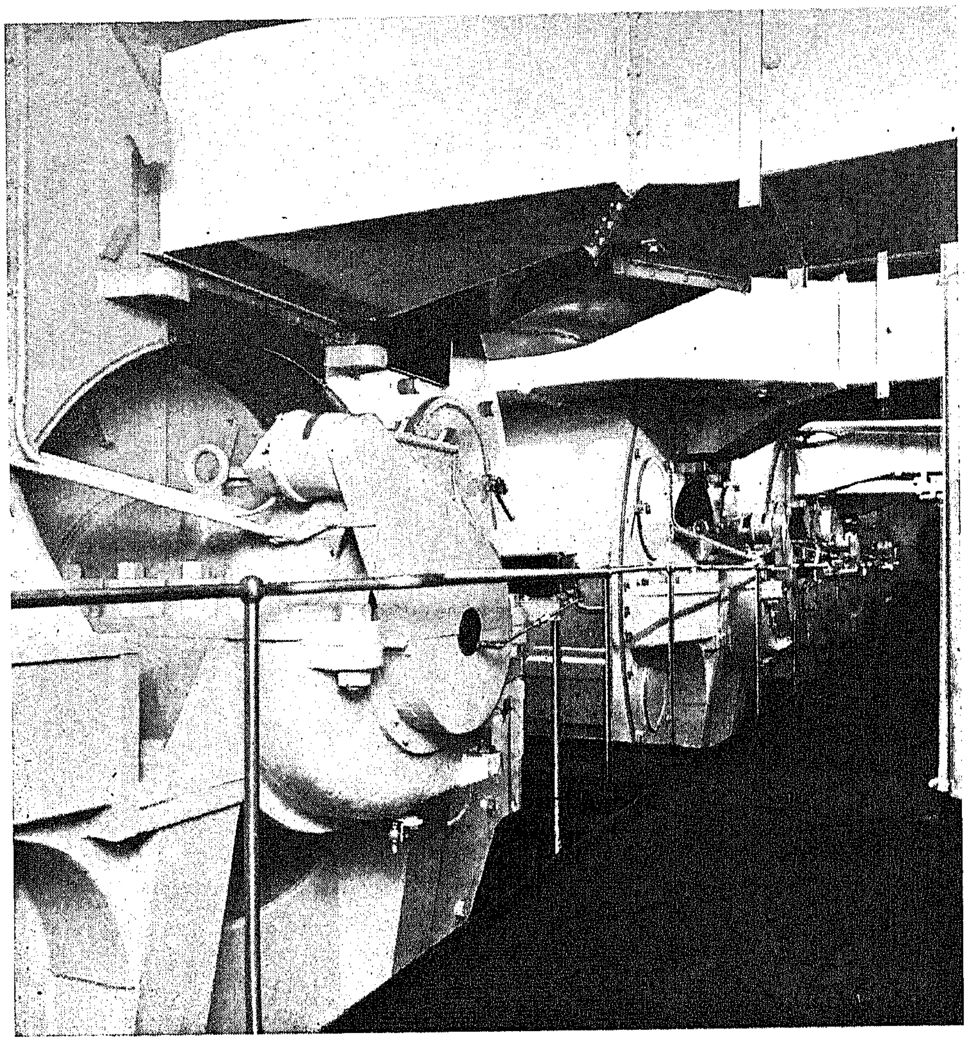

FIG. 6.—Four 4 750-s.h.p. propulsion motors, showing disc-lubricated bearings and ventilating trunking. The small generators on bearings are for operating speed indicators.

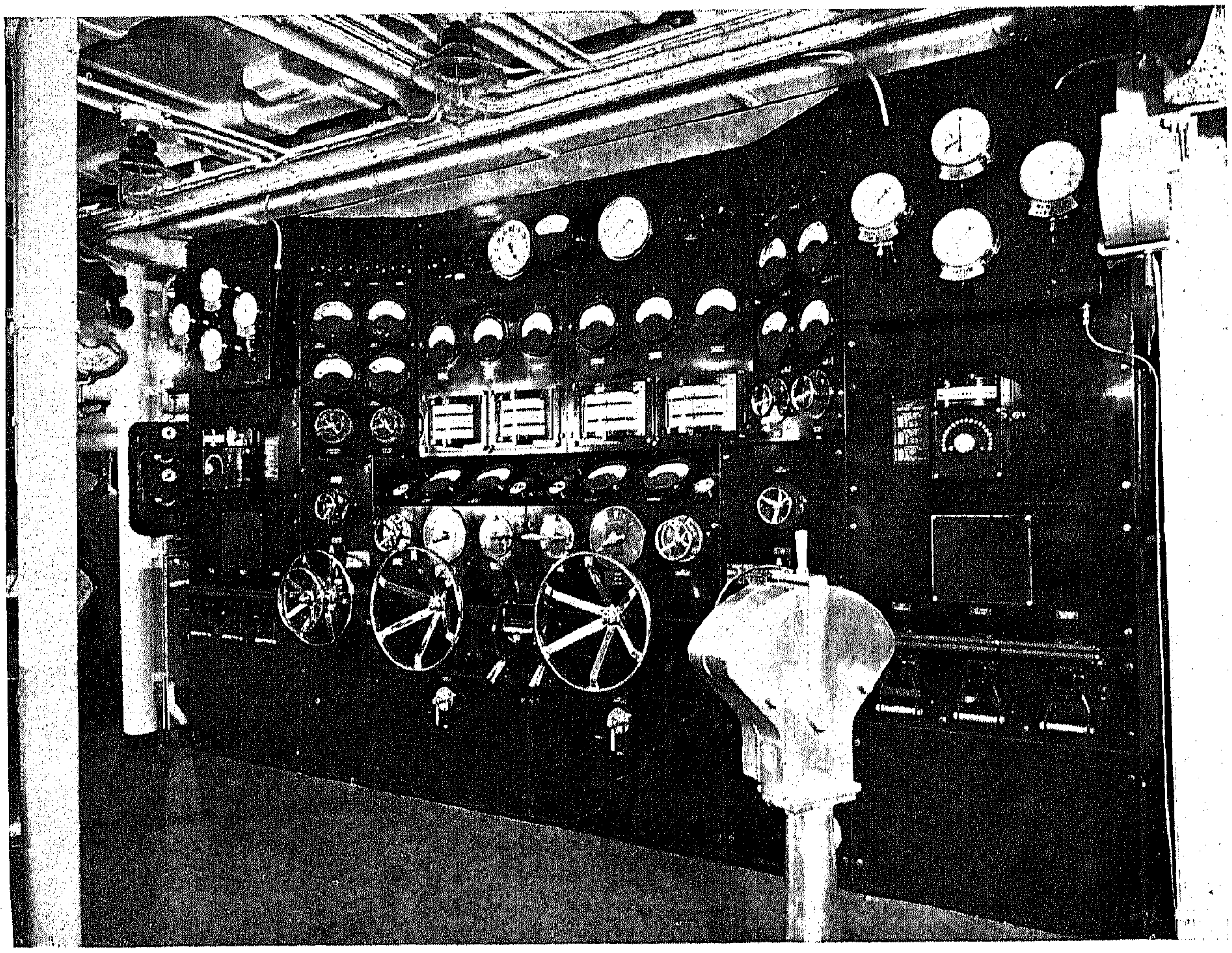

FIG. 8.—Starting platform of 3 000-volt 3-phase 50-cycle propulsion control equipment.

against breakdown. The motor may also have a double armature. All the armatures are connected in series and provision can be made for immediately cutting a generator out of circuit in case of failure.

This can be done by providing a make-before-break change-over selector switch, with suitable auxiliary contacts which first open the field of the generator to be isolated. Sequence catches then arrest motion of the switch in order to permit the residual field to die away, after which the operator completes the movement, temporarily short-circuiting the generator armature, completing the propulsion circuit through a direct connection, and finally opening the generator armature-circuit. Auxiliary contacts on the generator field contactors are arranged to open a short-circuit across suitable resistance in the motor fields, in order to permit them to take up, on the reduced voltage available from one generator, a speed which will absorb the full horse-power of that engine.

If there are two engines and one breaks down, the voltage supplied to the motor is halved and the propeller runs at half speed. The horse-power required at half speed, however, is only one-eighth of the full-load horse-power, so that the propeller must be speeded up to about 80 per cent of full speed. This brings the load up to half full load, which is the full output of one engine.

Where more than one generator is running on one propeller, arrangements can be made, under a patented system, for automatically cutting out a failing generator and adjusting the motor field value to suit the full output of the remaining engine or engines. For this purpose a special differential relay is provided, which balances the voltage of one generator against that of another in the same system, a contact on the lower-voltage side of the system being provided to open the generator field contacts of the failing machine, thus leaving a dead armature in the circuit, which can then be isolated by means of a change-over make-before-break switch, as described above. Under-speed contacts on a faulty engine can also be arranged to open the field circuit of its co-related generator. Thus a failing engine can be removed from service with the remaining power uninterrupted.

Twin-screw.—Under another patented system of protection, similar arrangements will permit the removal of a failing engine on twin-screw systems, without total loss of power on either side of the vessel. This is done by normally operating the two sides of the vessel independently, but with the system connected on a 3-wire scheme, having an automatic switch inserted in the mid-wire connection. Failure of an engine on, say, the port side is arranged to operate either a reverse-power relay or an underspeed device on the port generator, which will trip the generator field contactor and also open the mid-wire circuit breaker. The two motors are then left in series with each other, operating from the starboard generator through the dead armature of the port generator, which can be isolated by means of a change-over make-before-break switch.

This scheme is possible with twin-screw vessels operating with two engines, when the reversal is carried out at the motor field, as the flow of current is always in the same direction. It should be noted that the mid-wire carries current only when the two motors are running at different speeds.

For normal running in twin-screw vessels, it is usual to keep the port or starboard sides separate. It is advisable, however, to be able to run both motors in series with one generator if required. In this case both propellers must run at the same speed, but one can be ahead and the other astern.

When the two motors are connected in series, a difficulty arises with regard to racing. For example, the port propeller may come out of the water before the starboard. The port motor will then begin to speed up and the current will be reduced. The starboard motor will thus fall in speed, until finally there is a tendency for it to reach the trailing speed of about 70 per cent. The port motor will therefore tend to reach 130 per cent of the full speed available with one engine in order that the sum of the counter-e.m.f.'s of the motors may equal the generator voltage.

Constant-Current Systems.

Another system which has been proposed instead of the Ward–Leonard is the constant-current system (see curve *c*, Fig. 10). In this system the machines are so designed that a practically constant current flows in the main circuit. Speed regulation is effected by varying the motor field. At starting, the motor field is zero, so that the armature current produces no torque. As the motor field is strengthened, the torque is increased and the speed of the propeller rises. The generator voltage automatically rises with the propeller speed.

There are four principal methods employed on the so-called constant-current system.

(*a*) The first uses the 3-field generator, which has a separately excited winding, a self-excited winding, and a counter-compound winding. This machine gives a practically constant current over the working range, but the open-circuit voltage is rather high.

The condition of the propeller coming out of the water is entirely different from that of the Ward–Leonard system. The generator is designed to give constant current, and therefore continues to supply this current. The motor therefore continues to exert torque with the propeller out of the water. Consequently, the speed rises until the counter-e.m.f. of the motor is equal to the open-circuit generator voltage. It is a simple matter, however, to arrange a relay which will open the separately-excited generator field when the propeller speed rises a small percentage above the normal. This cuts down the current, and with it the torque.

With the 3-field generator it is possible to arrange the windings in such a way that the current carried when the voltage is reversed is considerably reduced. This condition occurs when the telegraph is moved quickly from "full ahead" to "full astern." When the motor field is reversed with the motor still running ahead, the voltage is reversed and power is taken from the propellers and absorbed in driving the engines. Under this condition, the generator can be designed to take such a current that the reverse power is only that required to run the engines light at their normal speed.

(*b*) In the Austin system (curve *d*, Fig. 10) the generator has specially-shaped pole shoes. The characteristic is similar to that of the 3-field generator over the working ranges, but the open-circuit voltage is lower. It is claimed that the speed-rise with the propeller out of the water is not excessive.

(*c*) A third system employs standard generators and uses a current relay which automatically regulates the generator field. If the current tends to rise, the generator field is weakened, and vice versa. With this system it is necessary to limit the generator voltage in order to prevent racing.

(*d*) A fourth system has been called the "controlled current" system. In this system a 3-field exciter is used, the counter-compound winding of which carries the main motor current. The characteristic is exactly the same as that of the 3-field generator. Regulation is effected on the exciter field instead of on the generator field.

In a single-screw ship with a constant-current system, more than one generator can be used, as for the Ward-Leonard system. In the 3-field and the Austin methods, the generators are connected in parallel, and in the relay method they are in series.

In a twin-screw ship, the port and starboard sides can either be kept separate, or the propeller motors can be connected in series. The latter method presents some advantages, and the two motors can be controlled entirely independently in speed and direction by means of the field regulators. In a rough sea, however, the method may involve a difficulty. If the propellers are coming out of the water they may not come out at the same time. When one propeller comes out, it is necessary to reduce the armature current and prevent racing. Since the two motor armatures are in series, however, the current in the other is also reduced and the driving power of the ship is lost. When the first propeller has entered the water again, the second may have come out, and the driving power is again lost. In this way, the power to drive the ship may only be available for a short proportion of the total time.

Response.

There is an interesting point with regard to the operation of the Ward-Leonard and constant-current systems. With the Ward-Leonard, the propeller speed quickly follows the telegraph orders. If the telegraph is changed from "full ahead" to "half ahead," the regulator is quickly changed to its "half ahead" position. Reverse power will flow from the motors to the generators, and the propeller speed will be quickly reduced.

The same change of order with the constant-current system will quickly reduce the motor-field regulator to the "half ahead" position. The torque is therefore reduced, but it remains in the same direction. The propeller speed will fall to slightly above the trailing speed and will gradually fall to half speed as the ship loses way. This difference in response will of course be readily recognized by the navigator. If a quicker response is required with the constant-current system, it is only necessary to put the telegraph "astern" until the ship loses way, and then come back to "half ahead."

CONCLUSION.

It is very gratifying to know that the standards and margins that the electrical industry has observed for many years have enabled marine engineers to accept electrical equipment without any criticism as to its reliability. It has taken a long time to become established on board ship, and this has only been achieved by the use of the best of workmanship and material, by the thorough manner in which electrical designers have tackled the problems involved, and by the co-operation of the marine engineers.

The thanks of the electrical industry are due to the marine engineers for this co-operation, without which the progress which marine electrification has achieved during the past 25 years would have been impossible.

The authors wish to thank the British Thomson-Houston Co. for the loan of slides, the General Electric Co., Ltd., for permission to publish some of the information and illustrations used in this paper, and their colleague Mr. H. J. Coates for his valuable assistance in its preparation.

DISCUSSION BEFORE THE INSTITUTION, 22ND NOVEMBER, 1934.

Mr. A. D. Constable: The authors have attempted a difficult task in dealing in a single paper with so very extensive a subject as this, as almost every phase of electrical engineering is concerned. Although it is impossible for them to go very much into detail in many of the sections, they have succeeded in presenting an excellent picture of the electrical equipment of a ship as a whole. The use of electricity for auxiliary drives in ships has had a very hard fight to get proper recognition, partly owing to the conservatism of shipowners and marine engineers (for which they are not much to be blamed, bearing in mind the extreme importance of dependability under all circumstances), and partly owing to the not very satisfactory designs of the earlier marine equipment, for which perhaps there is not quite so good an excuse. The rapid adoption in recent years of internal-combustion-engine propulsion has, however, forced the pace. In a ship so equipped there is no really practicable alternative to the electric drive for the auxiliaries. The result is that the use of electricity for driving the auxiliaries is now accepted as a general policy. In a large ship the extent of the use of electricity is equivalent to that in a small town. In view of the extreme importance of continuity of supply under the onerous conditions existing at sea, the design and lay-out of a ship's installation has to be very carefully considered—probably a good deal more so than in the case of a shore installation. The authors refer to the necessity of excluding oil and dirt from the dynamos and motors. The Admiralty have met that difficulty by putting in pipe ventilation, taking air from a clean source for the dynamos and larger motors. In the case of the smaller motors, totally enclosed self-cooled machines are largely used where weight permits. This procedure could with advantage be extended, and even in some cases to the control gear. The frequent cleaning and overhauling of dirty gear is apt to do more harm than good. It is general experience that well-designed and well-made electrical apparatus is better left alone between the periods of periodical major overhaul. As the authors say, direct current is almost exclusively used for ship work. The Admiralty have considered twice during the last 12 years the relative advantages of direct current and alternating current, and on each occasion they have come to the conclusion that, having adopted direct current, there is not sufficient justification to go over to alternating current. The balance, however, is so even between the two systems that, starting afresh, it would be just as profitable to use alternating current. I think that in some recent liner installations the limit has practically been reached for direct-current distribution. The current to be distributed at the low voltage which is essential for direct current is so large that the amount of copper required in cables, switchgear, and commutators, becomes almost prohibitive. When an a.c. supply is used it is very easy and economical to transform from a comparatively high generated voltage to the low voltage required locally. With proper safeguards there is no real objection to having a moderately high generated voltage; values of 5 000 volts and over have been adopted for ship propulsion equipment. It is understood that in such cases no one would ever work on live gear. The paper contains a very impressive diagram of a main switchboard. Perhaps because I am more accustomed to warship practice, I feel that such a concentration of switches and cables is out of place in a ship. In a warship, which has to be designed with a view to possible local damage by gunfire, it is necessary to split up the dynamo power into units distributed round the ship, so that not many can be put out of action by a lucky hit. For the same reason the feeders are tapped off the busbars all round the ship where the supplies are wanted, the busbars in naval ships taking the form of armoured cables. I think it would be more economical and otherwise of advantage to decentralize the distribution in mercantile ships. Greater use would be made of sub-switchboards in this case. To the objection that this makes supervision more difficult my reply is that very little supervision is required for switchboards, and if central control is considered desirable it is very easy now to get satisfactory distant-control switchgear. I rather visualize an installation more on the lines of that of a warship, of course using open-type switchboards properly protected from unauthorized interference. The authors stress the advantage of the group starting system for motors. This involves a good deal of complication in the wiring and switchgear, and the authors themselves remark that simplicity should be maintained in the equipment of a ship. Whilst one can design electrical gear which works with almost human intelligence and with superhuman precision, for ship work I prefer to adopt a gear of a simpler nature which requires to be supplemented by actual human intelligence to work it. The authors rightly refer to the importance of good cables, and mention that the Admiralty have had a good deal of experience of the performance of cables in ships. It is, I think, fair to say that in the past the majority of the troubles which have occurred in the electrical equipment of ships were due to cable faults. "Blow-outs," earths, bad insulation on the exposed ends, and cracks in the sheathing, used to be of common occurrence. After a long investigation which the Admiralty undertook in conjunction with the cable makers, a very much improved type of cable has been adopted in warships, and there is no reason why this type should not be used in mercantile ships. Although these cables will no doubt last very much longer than earlier types, I do not think they represent the final type for use in ships. In warships, weight is of very great importance. In some of our recent cruisers, comparatively small ships, some 120 tons of lead-covered cable have been installed. It would be a considerable advantage if we could reduce that large weight. For instance, for every ton of cable saved one could put in 27 sq. ft. of 2-in. armoured deck, or carry 16 rounds more of 6-in. gun ammunition. The weight of the lead is excessive, and from that point of view it is the most unsatisfactory material one can use for covering a cable. Lead is the heaviest common commercial metal, and also the weakest. All that is required is a very thin sheath of lead, as thin as can be extruded on to the cable, which will suffice to keep out air and moisture. If this is covered with an armouring of wire the result is a cable which is much lighter than the normal type, and also much stronger. Such a cable would also be suitable for a mercantile ship. Suitably filled wire braiding also serves as a fairly good fire-resisting protection; it prevents the rapid melting of the lead in a fire and consequent exposure of the rubber to the flame. Tests have demonstrated this feature satisfactorily. Another most important point in the cable system of a ship is proper planning at an early stage. Pipes, by reason of their comparative intractability, are given a large measure of respect; whereas any tortuous route is often considered good enough for cables. Cable runs ought to be settled at a very early stage in the building of the ship, and no cables should be put where they are afterwards inaccessible. In merchant ships much of the cable is concealed behind wood panelling, and any bad work in such positions is a serious potential source of danger. I do not know whether there is any proof that any of the recent disastrous fires in ships have been due to the popular explanation "the fusing of electrical wires," but there is a suspicion that cable faults may have caused some of the fires. It is very necessary, therefore, to take every possible precaution to avoid risk in that direction. Another point to be borne in mind is the fact that a ship at sea is not a rigid structure, and the working of the vessel in a sea may cause damage to cables if run without proper consideration of this feature. I believe, however, that the wiring in British ships is of a high order and is, in general, well looked after. In the section dealing with electrical propulsion the authors give an excellent summary of the various types of plant which have been used up to date. The convenience and flexibility of Diesel-electric equipment accounts for its adoption in so many small vessels. For the same reason, in addition to quiet and vibrationless running, the adoption of turbo-electric equipments in various passenger vessels has been justified. Moreover, in some of the turbo-electric vessels the ability to steam at normal speeds with part of the plant shut down, tends to economical running and to reliability in emergency. One feature of the paper which I do not like very much is the reference to many schemes of interconnection and to the many ingenious pieces of automatic control apparatus which have been used for special purposes in certain cases. I realize that in some cases these may have been quite necessary, but again I should lean to the side of simplicity. The fact that automatic electrical devices can so readily be added to an installation should not be made an excuse for accepting an arrangement of machinery which needs such delicate controlling apparatus, if more careful study of the possible alternatives will enable a simpler and more direct lay-out to do what is required. In the case of a large liner which is to operate on the Atlantic routes, where a set schedule speed has to be worked to as far as weather permits when once the ship is in open water, it is not possible to make out a case for the adoption of electrical propulsion on grounds of economy alone if the same steam conditions are accepted. It does not necessarily follow, though, that one need adopt the same steam conditions. The possibility of grouping the turbo-alternators with their boilers in self-contained units with very short steam-pipes, irrespective of the position of the motors, may enable higher steam pressures and higher temperatures to be used with safety, and may even enable inter-stage reheating to be simply applied. There is the further possibility of arranging to supply the auxiliaries by comparatively large machines driven from the main turbines when they are up to steady speed. The combination of these possibilities will enable savings in fuel consumption to be effected as compared with a purely mechanical drive, which will considerably outweigh the extra cost of the installation. Even in a very large ship there is nothing to prevent an electric drive being adopted. Presumably the other considerations, apart from economy, are considered sufficient in the case of the "Normandie" to justify electrical propulsion. I am sure that all in this country interested in ships confidently hope that the all-geared "Queen Mary" will prove to be a faster and more economical ship than the all-electric "Normandie"; and I believe there are engineers in this country who, if given the opportunity, could design an all-electric equipment for the possible sister-ship to the "Queen Mary" which would make the ship still more economical and a more comfortable ship in which to travel. The question is, will the opportunity be given for such an excellent comparative trial?

Mr. G. O. Watson: I am somewhat disappointed in the paper, which would have been of more value had it contained a more critical and analytical view of some of the details. With regard to generators for propulsion, only a passing reference is made to the Diesel-electric alternating-current system. It is true that very little has yet been accomplished with this system, but in view of the fierce competition with other forms of drive electrical manufacturers will do well to study the problems involved. I am convinced that they are not insurmountable, and it is probable that a satisfactory Diesel-electric a.c. system would show a gain both in efficiency and in first cost. As regards the heating of machines to prevent condensation when idle, the alternative method of passing a small current through the field windings appears to be more sensible than installing separate heaters. Also, it is desirable to circulate the air, as otherwise the moisture will condense on the cold frame if the machine is of the enclosed type. Diesel-driven auxiliary generators appear to offer material advantages in an unexpected direction, such as in a catastrophe similar to that which recently overtook the "Morro Castle." In this instance the auxiliaries continued to run unattended long after the engine room became uninhabitable owing to smoke. The use of double-unit motors for d.c. propulsion purposes is mentioned in the paper. This is usually necessary in order to keep down the diameter, which in most cases is a limiting feature, and credit for the additional reliability of two motors, one of which is sufficient to drive the ship at approximately 80 per cent speed, is very rightly claimed. There is, however, an added advantage which has been overlooked; namely, that on the rare occasions when it is necessary to trim the commutators one half of the motor can be used to rotate the other half. Winch-control cables, where contactor gear is used, are a source of trouble owing to the inductive discharge from the contactor coils. It has been overcome by using cables insulated for 500 volts, where the circuit voltage is 220 volts. I should like to ask the authors whether they advocate time-delay devices for winches; in my opinion, as speed of working is here of primary importance, "current limit" as opposed to "time-delay" devices are essential. The former permit more rapid acceleration on light loads. Back-e.m.f. devices are unsuitable for ship work, as the line voltage is here subject to greater variation than on land. When contactor gear is used for continuously-running machines, a good form of notching relay is one which uses a combination of current and time-delay. The action is rendered slower by high accelerating current, but the device cuts out eventually, thus protecting the starting resistance. A disadvantage of the plural-starter or uni-start systems is that with these a slightly longer time is taken to restart all the motors after a total shutdown, as only one motor can be started at a time. Switchgear designers should remember that, except in ships fitted with emergency generators, the busbars can very rarely be made dead. Accessibility should therefore be the keynote. Circuit breakers and switches with connection studs 1½ in. or so in diameter are only too common; the nuts, if they work loose (as they frequently do), are almost impossible to tighten on a live board. The design should be such that the connections are made with two or more bolts not exceeding ¾ in. diameter. We are told in the paper of the enormous variety of applications of electricity in a modern passenger vessel. The electrician in charge of such plants is responsible not merely for the generating plant, but also for the distribution system and the consuming apparatus. So far as motors are concerned, the schedule given in Table 2 is not exceptional for a modern 20 000-ton passenger liner, and the use of electrically-driven auxiliaries for all classes of vessels is now practically universal. It is somewhat surprising, therefore, that although marine engineers are required to pass Board of Trade examinations there is no such test of the qualifications of the electrician. It is true that the engineer has to answer electrical questions in the course of his examinations; nevertheless, very few marine engineers would be capable of dealing with some of the more complicated switch and control gear in the event of a serious breakdown. The responsibility therefore falls on the electrician. How, under present circumstances, is a shipowner or superintendent to choose his electricians? In my opinion there is urgent need for the creation of a class of certified electricians for operating the very large electrical installations of modern ships.

Dr. C. C. Garrard: The authors would have been justified if they had displayed great enthusiasm regarding the results they have achieved in connection with the marine applications of electricity, some of which are given in the paper. For myself, I think the reticence they have shown and the modesty of their statements render the paper the more valuable. Marine engineers and shipowners know their jobs, and if they are to be convinced the electrical engineer must be very sure of his facts and be prepared to prove them up to the hilt. This attitude of mind is sometimes ignored by too-enthusiastic advocates of electrification.

The authors rightly draw attention to the great incidental advantages which electric propulsion affords in addition to the primary one of efficiency. The possibility of making up time is one of these, just as it is with electric railway traction. Further, it has been proved that an electrically-propelled ship can maintain its schedule speed in weather conditions which would render this quite impossible with a direct steam drive. The cushioning effect of the air-gaps of the motor and generator between the propeller and the prime mover is very important. I am in full agreement as to the great advantages of fully automatic starting gear for all auxiliaries; in fact, I think the principle could be well applied to the propulsion gear itself. In this connection it seems to me there is a slight inconsistency, as the authors advocate contactor gear in general yet have not applied it to the interesting plural-starter equipment which they describe. The statement on page 250 regarding ships' cables is remarkable. In land practice the rate of depreciation of cables (as shown by the time allowed for the amortization of loans) is generally regarded as among the lowest of all plant. Why is the figure different on a ship? Is it because of the way the cables are installed? There is generally a race between the various contractors, each trying to get his cables in the most convenient position first. There is much to be said for a proper lay-out of cable runs and for the abandonment of the haphazard system which has sometimes been in vogue.

It is clear that, having regard to the great convenience of the arrangements whereby the various items of the propulsion machinery can be interconnected, relatively great simplicity has been attained. I would plead for still greater simplicity, however, and I would ask whether the alternative direct mechanical control described on page 255 is really necessary or desirable. Is this not something in the nature of a concession to underwriters and the like, who have the idea that electrical plant is unreliable? The facts are, of course, the reverse of this. With the control arranged in the manner so rightly advocated by the authors, whereby access to any part may be obtained without stopping the ship, it seems to me that alternative mechanical operation is a totally unnecessary insurance.

I take it that the follow-up control, also described on page 255, is such that the speed of operation of the generator field regulator depends upon the electrical conditions in the main circuits and not only on the speed of the regulator motors. I suggest that this should be made clear in the main paragraph.

In conclusion, I would say that this paper comes at a very opportune time, in view of the revival in shipbuilding which appears likely. Naval architects should consider electric propulsion for any ship they may be designing: for large vessels the advantages to be obtained from it are overwhelming. To mention only one relatively small class, that of tugboats, which is the most recent development of electric propulsion in this country; the Diesel-electric system for these vessels provides such economy and ease of manœuvring that I am convinced that any owner who has acquainted himself with the facts will not hesitate to adopt the system for any such ships he intends to have built.

Dr. W. G. Thompson: One is tempted to inquire into the features of the electric ship which have made it such a conspicuous success, as indicated by Table 1. Arguments were formerly advanced in favour of the grouping of machinery, the reduction in the amount of line shafting between the propeller and the engine, and the more flexible control between the driving prime-mover and the propeller. It was also suggested that the turbo-electric ship should show an advantage even over the geared steam turbine, despite the efficient high-pressure turbine running at a higher geared speed than the intermediate-pressure and low-pressure turbines. The illustrations indicate the very clean lay-out for the electric ship and the absence of the astern and the low-pressure turbines and cross-over piping which are necessary when arrangements have to be made for astern running with the prime mover. It would be interesting to know whether these purely technical considerations have had any serious influence on the development of the electric ship. Turning to Table 2, I have always been struck by the amount of space taken up in the auxiliary engine-room by the direct-current Diesel-driven generator sets. In view of previous speakers' remarks I do think that the alternating-current system of auxiliaries should be seriously considered. At the foot of page 243 reference is made to exhaust-heated boilers for driving auxiliaries. I believe that the employment of such boilers for driving auxiliaries has been found to be somewhat costly, even in the case of the 4-stroke Diesel engine with its high exhaust temperature. Turning to Part 2 of the paper, the authors refer to the hull machinery, and also to the steering gear. They rightly point out that it is the introduction of the direct Diesel-driven type of ship which has brought about a considerable development in the application of electricity to ships' auxiliaries. One would have thought, however, that this would have been justified in any case from the point of view of the steering gear. Electrical steering-gear has been taken up with considerable avidity by foreign competitors, and there has been in many cases a corresponding reluctance on the part of British shipowners to adopt such gear, which can show considerable advantages over steam steering-gear. There are data to show, for example, that the power consumed by electrical steering-gear is only about one-tenth of that consumed by steam steering-gear. Taking the case of a ship of the "Bremen" class, the rating of the steam gear would be of the order of 1 000 h.p.; yet an electric gear would perform the same function successfully when taking an average load of 50 amps. at 220 volts. I saw figures recently of the maintenance costs of 10 years' operation of electrical steering-gear; the cost of the renewals was less than £1. Deck machinery has undergone considerable improvements since attempts were first made to introduce the electric motor. The original motors suffered from jerky starting; modern motors, however, give a flexibility which is comparable with that of some of the steam winches, and have been designed so as to stall at 50 or even 100 per cent overload. Turning to Part 3 of the paper, it would be interesting to know to what extent the economies of the shore power station have been carried over into marine practice. Can the authors say whether a consumption of 0·45 lb. per s.h.p. has been obtained in a turbo-electric driven ship? Six or seven years ago figures of weights were quoted in regard to turbo-electric machinery, and 39 lb. per s.h.p. was suggested for a large liner of the type referred to in the paper; it was possible, I believe, to reduce that figure to 18 lb. per s.h.p. in the case of a war vessel. I should be interested to learn whether any of the modern ships referred to in the paper have figures in agreement with those. The figures at the bottom of page 253 regarding the shaft horse-power taken by the various alternating-current motors are very interesting. Torsion-meter readings have not always proved satisfactory, and the possibility of obtaining absolute data as to what is meant by shaft horse-power is one of the great advantages provided by electrification. In regard to the turbo-alternator drive, it is interesting to note how the synchronous machine has displaced the variable-speed induction motor. I am interested in Fig. 9; in this connection, how many seconds elapsed before the ship was actually moving astern? Reference is made to the direct-current Diesel-electric drive; at the time this was first being proposed in this country considerable opposition was met with in shipbuilding drawing-offices, largely because the people in charge had marine experience and were naturally rather doubtful of the capabilities of deck officers to operate the main machinery, even through a control relay. The manner in which the difficulty has been overcome is an excellent tribute to the ingenuity of the electrical engineer. I should like to ask a question about the reference to racing which is made on page 258. Apparently the kinetic energy of the propeller which comes out of the water is immediately transferred to the immersed starboard propeller. Is it necessary to apply the helm in order to counteract this effect? Remembering the amount of propaganda which was put forward 10 years ago in favour of the direct-driven oil-engine vessel, and the achievements set out in this paper of the turbo-electric vessel, I think the authors are extremely modest in their claims for the electric ship.

Dr. S. Whitehead: Further mention might be made in the paper of the problems of cable operation and installation. A number of problems have been placed before the Electrical Research Association during the last few years by those who are interested in the use of electricity on board ship, and it may be of interest to give a general description of the nature of these questions and the general type of answer which it is possible to put forward. First of all, as regards large single-core cables carrying alternating current, some concern was felt on three aspects of normal runs. The first is the question of the impedance voltage-drop; this may be very considerably increased by the bulkhead along which the cable is run, the increase amounting to 50 per cent or more; but since the runs are very short this is probably not a serious matter. The second question is how far the steel of the ship may become warm; fortunately, such heating is probably quite small. The third question is how far the rating may be reduced. On this question the I.E.E. Wiring Regulations contain a good deal of information; the effect is not great. From that point of view it is better to run the cables so that they are either in actual contact with the bulkhead or are separated from it by a considerable distance. Another matter which is possibly more important is the question of the passage through bulkheads of large single-core cables carrying alternating current. The problem here is that the bulkhead will become quite hot if only a very small clearance hole is used, together with an ordinary steel or cast-iron gland, and it will also become hot if a non-magnetic gland is used when the clearance hole in the bulkhead itself is quite small. A non-magnetic gland of reasonable dimensions will obviate the difficulty so far as the electrical heating is concerned. A point in the early part of the paper which interests me is the very wide range of ambient temperature which is to be encountered in ship cable installations. Have any special measures been adopted in order to economize on the reduction in rating of cables which must frequently occur? For example, it is not very economical to use rubber-covered cables at ambient temperatures above 105° F.; and in the same way at 140° F. (one of the temperatures mentioned in the paper) even paper-insulated cables will have their ratings reduced. This again will not be very economical so far as the copper is concerned. What is the authors' opinion as to the growth of the use of alternating current as opposed to direct current on board ship, and what are the prospects of the further development and use of cambric-insulated cables on ships?

Mr. A. C. Hardy: I should like to describe the attitude of the marine engineer to the electrical engineer. The marine engineer is apt to regard electrical plant as a pure necessity rather than with any particular friendliness. The reason for this is that the marine industry is a very self-contained industry with its own boiler-shops and engine-shops. On the other hand, electricity—particularly in association with the Diesel engine—has provided flexibility, fuel economy, savings in wages and crew, etc., which are absolutely necessary in these stringent days of shipping competition. Electricity cannot, therefore, be entirely neglected. It is up to the electrical engineer, nevertheless, to provide equipment which is reliable and which can be purchased at an economical price. That may be difficult because electrical equipment is a luxury article. It is a tribute to the electrical industry, however, that of the two biggest ships now being built one is propelled by turbo-electric propulsion. Also, on the Clyde, where there is more conservation in marine engineering than anywhere else in the world, electricity has now broken into the propulsion market, in the driving of paddles—one of the oldest of steam strongholds—by electric motors in association with Diesel engines. These two factors alone, in association with the enormous strides being made in the use of electricity for auxiliary purposes, are straws showing the direction in which the wind is blowing.

Mr. H. W. Beara: The authors mention the value of wattmeters indicating the shaft horse-power of each propelling motor; such instruments afford by far the most accurate means of determining the propulsion power during the ship's trials, for comparison with the figures predicted from tank tests of the model hull.

Another aspect of the value of such instruments is given in the normal running of the ship in service. I have met with a case where, in a twin-screw turbo-electric ship, a 15 per cent reduction of power below normal, taken by one propelling motor, indicated a damaged screw propeller; this diagnosis was subsequently verified by examination in dry dock.

I am pleased to see the stress laid by the authors on the importance of apparatus on the feeder panels of the main d.c. switchboard to discriminate between essential and non-essential power circuits; the engine-room and navigation requirements must be maintained at all costs, and other circuits according to their relative importance.

In my own experience, such a scheme proved invaluable when, owing to failure of a boiler feed-pump supplying water-tube boilers, furnaces had to be extinguished and the output of the auxiliary steam-driven generators fell right off with the rapidly dwindling steam pressure and vacuum. To add to the difficulty, the Diesel engines driving the stand-by auxiliary generators refused to start readily, and the ship was soon in darkness. In such circumstances the separation of essential and non-essential circuits greatly facilitated switching operations.

I view with misgivings the proposal to use a common set of starting gear for a number of engine-room and boiler-room auxiliaries. Simplicity should be the keynote of the engine-room electrical equipment.

With regard to cable faults, some of the previous speakers evidently do not realize the great difference existing between a land and a sea-going installation. It must not be overlooked that a ship is by no means a rigid structure, but is "flexing" the whole time it is at sea, and cables must be designed and installed to withstand movement of this sort. Ships' electricians know to their cost that cable earth-faults are far more numerous for the first few days at sea after a period in dock, and also during bad weather, than at any other time. I refer to cabin wiring in particular; however, I understand that cable makers have now introduced an improved lead-alloy sheath which is less liable to deteriorate with vibration.

In conclusion, I am glad that Mr. Watson has raised the question of the qualifications and status of ships' electricians; they have increasingly great responsibilities with such a wide range of electrical apparatus and machinery to maintain in order as the authors have shown to be installed on shipboard. I shall be very pleased when the Board of Trade recognizes that a qualifying examination and certificate is as necessary for the ship's electrician as for the marine engineer.

Mr. S. H. Chase: I am a little disappointed to find that neither in Table 2 nor in the long list of miscellaneous equipment for a modern ship given on page 250 is any mention made of batteries, because for a number of years batteries have been used on board ship for operating bells, fire alarms, telephones, and emergency wireless services. The authors do, however, make two references to the "battery" in connection with stand-by services, and I take it for granted that they agree that a battery should be provided for the services mentioned in the paper.

There has recently been a very distinct move towards providing batteries for taking over emergency services, but I would suggest that the capacity of the battery should be larger than that mentioned in the paper, to enable it to take over the steering facilities for a few minutes. In my opinion, a battery capable of doing this for at least half an hour, and also of looking after the essential emergency lighting, particularly in the engine room, is the minimum that should be provided.

They mention, too, that direct current has been almost universally employed for auxiliary purposes, and that generally the circuits are divided at the main switchboard into essential and non-essential groups, and, in consequence, these lend themselves very suitably to the use of a battery. In at least two of the liners mentioned in the paper such a battery equipment has been provided, and in these cases the battery automatically takes over the essential services until some other auxiliary set is started up, or, as a last resource, the Diesel set on the top deck is put into operation.

The electrical equipment of cargo vessels is also mentioned; a number of these are now equipped with a battery to provide the lighting required in port when the auxiliary sets are shut down and the stevedoring services are finished.

Mr. W. McClelland: My acquaintance with the subject dealt with by the authors has been obtained in connection with the electrical equipment of warships. I have been on board each of the mercantile ships named in the paper, and have had opportunities for discussing their performance. I can say that all are highly efficient, economical, and thoroughly satisfactory.

On page 242 the authors make a reference to Diesel-driven auxiliary generators, and state that there is much to be said for the use of such machines even where steam is employed for the main propulsion. My own view is that, in a steam-driven ship, it is far better whilst the ship is at sea to employ steam-driven electric generators, augmented by Diesel-driven generators in case of extra load. The power of the Diesel generators should be such that they can take the harbour load when the boilers are shut down. My reason for holding this view is that low-speed Diesel engines are heavy, and take up a great deal of space. High-speed Diesel engines at the present time are run at excessive speeds and are much over-rated; the result is that the cost of upkeep and the liability to breakdown if run continuously at full rated load are very great.

On page 244 the authors refer to the tendency of naval architects and shipbuilders to limit space for the engine room. I heartily support their appeal to naval architects and ship designers to give more space. There is no doubt that the machinery in many ships is altogether too cramped.

With regard to the electrically-driven steering-gear, the authors state that there is always one motor available for stand-by purposes. I notice that the system of distribution is by means of a main switchboard and various sub-switchboards; and it may be that the steering gear is connected to one of the after sub-switchboards. It seems to me that the connections to these two motors, one of which acts as a stand-by to the other, should be taken from different parts of the supply system in order that there may be a small risk of total breakdown.

The authors refer also to the method of control for the windlass and the capstans. I prefer the Ward–Leonard control system for heavy machinery, such as the forward capstan in the ship. The booster control is certainly lighter; but I have had long experience of the Ward–Leonard control for these heavy duties, and it has been found to be thoroughly satisfactory and reliable. Although in the paper it is stated that the booster system is a development of the Ward–Leonard system, these two systems were actually employed as far back as 1899 in two ships—the " Powerful " and the " Terrible." Of the two 9·2 guns on those ships, one was run by the Ward–Leonard system and the other by a booster system very similar to that in use for various ship's services to-day. The advantage of the Ward–Leonard system is that the whole speed control is taken on the field system, whereas for reversal by the booster system the armature circuit has to be reversed.

Several speakers have referred to the multiple starter; I quite agree that we ought to aim at simplicity. It seems to me that it will be necessary to have a large number of motors in close proximity one to the other if one is to reap any benefit from the plural starter. We first have the plural starter; then the selector switches, cables running from each motor to the central point, and a motor-driven controller to regulate the speed of starting according to load. It seems to me that with all this complication there will not be much saving in weight, and possibly not much in space.

With regard to the use of ball bearings for motors for marine work, the authors recommend that journal bearings should be used where a certain degree of silence is necessary. When I was at the Admiralty we had a considerable amount of experience with ball bearings in machines placed aft in the steering-gear compartments, and we found that where the machine was not constantly in operation, and was in a position where it was subjected to constant vibration, the movement, however slight, created " flats " on the ball races and balls. As a consequence we abandoned ball bearings and adopted sleeve bearings in steering gear and in compartments subject to constant vibration.

The authors refer to the experience of the Admiralty with cables. It is true that the Admiralty, in conjunction with the makers, have devised a cable which is expected to have a very considerably increased life. Originally pure rubber was laid on between the core and the vulcanized rubber. This pure rubber permitted vulcanized rubber of varying qualities to be supplied, and during the tests at the maker's works it was very difficult to detect inconsistent qualities of the vulcanized rubber. The pure rubber has now been abandoned, and instead a layer of tin-foil has been placed between the core and the inner side of the vulcanized rubber. The tin-foil beds itself well into the underside of the vulcanized rubber, preventing the ingress of atmospheric oxygen, and thus obviating—to a large extent—deterioration. The Admiralty have also adopted a new ternary lead-alloy for the sheathing of the cable, and this is proving very satisfactory in withstanding the effects of vibration. It is much superior to the pure lead sheathing formerly used.

Mr. P. F. Grove (*communicated*): It is very gratifying to find that the hard work done by the electrical manufacturers since the war has now achieved results in the form of the almost universal use of electricity for general purposes and the increasing favour for electric drive.

The Diesel ship has done much to promote this use of electricity, although it has been a serious competitor as a means of propulsion. The Diesel ship is now on the decline, but has again contributed to the welfare of electric propulsion by assuring marine engineers of its reliability as a prime-mover for Diesel-electric drive.

The use of constant-speed steam turbines and Diesel engines for electric drive removes a number of serious problems, which must always be present in direct mechanical drives.

A definite advantage of electric propulsion is the possibility of adapting the driving speed to suit the best propeller characteristics, and the authors do well in drawing attention to this. This advantage has been pointed out to marine engineers from the beginning, but it does not often appear to have been given the consideration it merits. In the earlier attempts to promote electric drive much stress was laid on the advantages of shortened propeller shafting, but the stern lines of a ship are governed by propeller characteristics, which must be given prior attention. Considerable attention has also been directed to the advantages of control of the propelling machinery from the bridge, but this is more a matter of convenience than of technical merit and should be adapted to suit the class of ship. Now that the electric drive has established itself these advantages become incidental and should not be overstressed.

The authors might have mentioned that for direct-current propelling motors it is usual to provide rotating frames, to enable all the field poles to be accessible for maintenance.

The importance of cable lay-out has always been realized, but definite experience with drives installed will make it easier for electrical engineers to press for the co-operation which the authors have rightly demanded.

The paper makes no reference to the use of electricity in warships, a subject which is fully dealt with in Mr. W. McClelland's paper.* The general reliability of electrical apparatus on board ship has made it possible to introduce it into warships, but it appears that electric drive for warships will never be entirely satisfactory.

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* *Journal I.E.E.*, 1927, vol. 65, p. 829.

This is supported by the scrapping of electric drive by the American Navy.

Generally it has been considered that the advantages of electric drive are not prominent for very large liners on the Atlantic route, but its adoption for the " Normandie " is of prime importance and we hope will produce results to convince marine engineers that electric propulsion is no longer an experiment.

Mr. R. Reid (*communicated*): Electric propulsion for ships is becoming more common in the world, although still rare in this country. One of the reasons for this state of affairs is the idea, prevalent amongst marine engineers, that the suitability of electric propulsion is confined to large high-powered ships and to tugs. This is a mistaken idea; although the advantages of electric propulsion have been proved in these two cases, its suitability extends over a much wider variety of types, as a careful examination of its qualities will disclose.

To use power to generate current, and then transform the current into power to propel the ship, with the necessary losses at each stage, appears on the face of it to be self-condemned as foolishness when power can be used for propulsion direct, without intermediate steps. This is the view of the ordinary marine engineer, who concerns himself only with his engines and overlooks the fact that the ship is built to earn money, and any means that enables the ship to increase her earnings as a unit is an advance even though one step or branch in the process shows a loss. If the change results in increased earnings by the ship, it may justify the use of less efficient machinery.

The following brief statement will show some of the advantages to be obtained in different types of ships by the adoption of electric propulsion. It should be borne in mind, however, that each case should be examined and treated on its merits.

In passenger ships, electric propulsion makes possible a better arrangement and distribution of the propelling and auxiliary machinery, which in turn permits of improved arrangement of accommodation, thus increasing earning power. It is also possible that the weight of machinery and fuel may be less, which will result in reduced power being required.

In tugs, electric propulsion enables the power installation to be reduced for a given duty; for instance, where a steam tug would require 1 000 h.p. to give the specified tow-rope pull, a Diesel-electric tug would give the same pull with 750 to 800 h.p. In addition, the ease of handling is much in favour of the electric scheme, a matter of some importance when, as is often the case, a ship is being handled in confined waters.

In cargo ships, as compared with coal-fired steamships, a Diesel-electric scheme will enable the dead-weight cargo capacity to be increased by from 10 to 12 per cent and the measurement capacity by about 15 per cent. These increases are due partly to the lighter weight of the Diesel-electric machinery and also to the reduced weight of oil fuel compared with coal; in addition, elimination of coal adds the coal-bunker spaces to earning space. In comparison with a direct Diesel-engined ship the electric plant will probably cost less, and there will also be probably some increase in earning power, depending on the type of direct Diesel engine with which the comparison is made.

In the smaller class of trawlers little or no advantage is to be derived by fitting Diesel-electric machinery, as the cost is so much higher than for steam, while there are few advantages to be set off against this cost. In the large class of Iceland trawlers, where the ships are away from home for over 3 weeks, the Diesel-electric scheme enables the size of ship to be reduced if desired, while with the same power as steam it will increase the speed from $\frac{1}{2}$ to $\frac{3}{4}$ knot. This increased speed may mean a saving of time, amounting to a day on each trip.

Speaking generally, in all cases where the auxiliary load, especially in port, is large in proportion to the propulsion load, the fitting of Diesel-electric machinery gives economy in first cost and also in operating cost. In all cases the Diesel-electric drive enables standard (and therefore cheap) engines to be used of such speeds and design as will give economical generation in use as well as in first cost. In all cases it permits the propeller to be run at such a speed as will be most suitable for maximum efficiency, bearing in mind the conditions of ship speed and form. The use of Diesel engines for direct propulsion has resulted in the propeller speed being increased, with a consequent drop in propeller efficiency; this has been done in order to produce the engines at a reasonable price.

Mr. William Wilson (*communicated*): In devoting a section of the paper to the transmission of power by cables and wiring, the authors lead up to the subject of danger from fire, which has been mentioned by Mr. Watson and has attracted a great deal of attention within the last few years. It is inevitable that, following a disaster such as those we have become only too familiar with during recent years, attacks should be made upon the electric cable system by interested parties who are extremely anxious that blame shall be steered well away from their own particular direction, and preferably shall rest upon some inanimate object which cannot defend itself. As far as I am aware, no authoritative statement has so far appeared in defence of the cable, and by way of a contribution towards this end I have given a considerable amount of thought to this question of the electrical origin of fires, and have come to a definite conclusion on the matter. Now my experience while serving as a marine engineer in three deep-sea steamers has included cables and the repairing of breakdowns, and I have never known any event which even remotely risked causing a fire. In addition, I have discussed the matter frequently with marine men, and with cable engineers, and have never been able to discover a single authentic case where even a small fire was originated by an arc or leakage on board ship. I am convinced that under marine conditions, which prevent woodwork from being tinder-dry, it is all but impossible for a fire to be caused without the occurrence of a definite flame. Now nearly all fires on shore begin in masses of specially inflammable material such as those in chests of drawers or cupboards, and it is not until an expanse of flame has occurred in this way that the fire begins to spread. It then does so because the heat radiated from the original flame raises the temperature of adjacent combustible materials, such as the woodwork of floors, panelling and furniture, wallpaper, and even paint, beyond the carbonizing point. Gas therefore begins to be given off generally, the flow and conflagration of this gas converting the building into a large gas burner and propagating the fire with great rapidity. My conviction is that fires at sea are caused in exactly the same manner; but, since the spaces are much smaller and very much more confined, in the first place gasification sets in much more readily, and secondly, the Bunsen-burner stage is reached much earlier. The trouble has been accentuated within recent years by the adoption of wood panelling in place of the steel finish prevalent 20 years ago, and by the greatly increased use of shore furniture in the cabins. Consequently it is much more easy for a passenger's luggage to be ignited, for example by a dropped cigarette; and once this has got well alight, that portion of the ship becomes to all intents and purposes a gas furnace, rendering the seat of the actual conflagration unapproachable. I would commend this theory to the attention of the authors and marine architects generally, as it appears to fit the actual occurrences exactly.

[The authors' reply to this discussion will be found on page 282.]

East Midland Sub-Centre, at Loughborough, 23rd October, 1934.

Mr. F. Nicholls: I am particularly interested in the question of the auxiliaries. Some 15–20 years ago it was quite common on cargo and passenger ships to work the cargo by means of steam winches; all who are familiar with a steam winch know what a noisy piece of machinery it is. Later on, hydraulic machinery was substituted for steam-driven equipment. The great advantage of electricity for such auxiliaries is its silent operation: this is of particular value from the passengers' point of view. It generally falls to the lot of the junior engineer to effect repairs, and only those who have had experience in this direction can appreciate how difficult a job this sometimes proves to be in rough weather. The authors' slides showed us the methods which have been adopted to ensure reliabilty of the electrical apparatus.

A most noticeable improvement in an electric ship is its efficient system of ventilation. Another advantage of the electric drive is the ease with which power can be conveyed to any point on the ship. It is much easier to run a cable to a winch than to have to carry a steam pipe, which is always liable to give trouble, owing to the movement of the ship.

I am particularly struck by the authors' remark that a 21 000-ton ship may be stopped in 3 minutes, and I can appreciate how it could be done. The last ship in which I served was a turbine ship, and it could be reversed with ease in about the same time. The operation, however, imposes a heavy strain on the ship's structure.

When the operating data are being compared with the design data it is important that the trim of the ship should be considered, as this makes a considerable difference to her performance. I should like to ask the authors what formula or method is adopted in making the necessary calculations.

Mr. William Wilson: The subject of the paper represents the most recent victory of electric drive over purely mechanical operation. In spite of the notable advances made by electrical engineering during the years following the development of the electric motor, there still remained certain fields, of which the rolling-mill and the ship formed the principal examples, where conditions were so very severe that they could only be fulfilled by the proved robustness of the heat engine. The rapid progress that has been made, however, during the past 20 years, i.e. practically since the outbreak of the War, has enabled even these strongholds to be stormed and captured.

The authors emphasize the importance which attaches to the methods of control adopted for the electrical machines. In the case of propulsion, it has been shown to have been possible, by an effective use of appropriate control principles, to employ very nearly the standard type of motor and the standard design of turbo-alternator, with all their advantages of continuous reliability. As regards the auxiliaries, automatic control has enabled the motors to accomplish the maximum effort of which they are capable, while they are protected from any risk of overstress whatever the load may be and whatever the operator may do. With this assistance, the modern electric motor has proved itself more than the equal of the heat engine.

A further point of interest in connection with the developments described in the paper is their effect upon electrical engineering practice in other fields. When new requirements such as those dealt with in the paper have to be met, it usually happens that the new methods and gear which are devised not only fulfil the immediate purpose but are found to have useful application elsewhere. At least two examples occur in the paper, the most interesting in my opinion being the plural starter. Now that it has been produced and applied on the large scale indicated by the authors, it seems an obvious improvement which should have been employed quite widely years ago. I should like to ask the authors whether important applications of the principle have not already been made in industrial engineering. Another example of a change brought about by the methods described in the paper is the extended use of clockwork for delay purposes in place of the familiar oil dashpot. The latter must have been almost inapplicable under marine conditions, on account of the wide variation of ambient temperature that is experienced. In the case of one of the voyages described by the authors, the climate might be liable to change from a blizzard to tropical conditions in the space of something like a day, involving a variation of from 0° to, say, 40° C. in temperature. It is not generally realized how much the viscosity of dashpot oil of the usual consistency will vary over this temperature range; the change is actually sufficient to produce a variation in time-lag of something like 9 to 1. Such a regulation would be quite out of the question for satisfactory control purposes, and the change to a clockwork escapement is therefore to be commended. In consequence of their adoption for marine purposes, clockwork time-starters have to my knowledge been used in greatly increasing numbers for industrial control generally.

Mr. J. C. Heath: I should like to know the opinion of the authors as to whether the increase in the use of electricity on ships has anything to do with the fires that have recently occurred on various large liners.

Mr. J. F. Driver: The fact that most impresses itself on all of us when reading descriptions of the electrical equipment on some of the larger ships is that the total power dealt with is comparable with the output of a modern super power station, and yet the whole of the plant is stored in a very confined space.

On page 242 the authors mention that the voltage in the case of Diesel-electric d.c. propulsion may be as high as 1 200 or 1 500 volts. I should like to ask why such a high voltage is necessary. It would appear that the cable lines are comparatively short, and that the extra cost of copper would be small compared with the gain in reliability achieved by running at a lower voltage. The possible dangers of shock should also be taken into consideration.

I do not agree with the remark (page 250) that in the case of turbo-electric drive there is no reason why the frequency should not be chosen at any value. I suggest that there should be standardization throughout the world, and, as electricity on board ship is bound to become usual practice in the near future, harbours and docks should be able to supply current for all auxiliaries when the ship is in the dock.

I should like to ask the author's opinion as to the desirability of changing the regulations regarding the permissible temperature-rise of electrical machinery on board ship. It seems to me that the prevailing specifications are not in accordance with modern practice, in view of the fact that nowadays ships are better ventilated; if a higher temperature-rise were allowed it might be possible to reduce the dimensions of the apparatus, allow for more cargo space, and lower the cost of the plant.

Mr. J. H. R. Nixon: There can be no doubt that the use of electricity is firmly established for auxiliary services, but the question of propulsion appears to be more open. The owners of the "Queen Mary" have decided to use gear turbines, and interesting possibilities are opened up by the rivalry between this ship and the new French liner "Normandie," which will be equipped with turbo-electric propulsion. The available particulars relating to these two ships are very meagre, but on the lines of the authors' Table 1 the figures given in Table A are approximately correct. The faith of our French neighbours in the capabilities of turbo-electric propulsion is strikingly illustrated by the size and importance of the plant installed in the "Normandie," which has a total capacity of nearly 150 000 kW, the equivalent of our largest British super-power stations. Her career will be watched with deep interest by engineers throughout the whole world. When at length the "Queen Mary" enters into the Atlantic service, the comparative performance of the two ships will afford a valuable demonstration of the relative merits of the systems of propulsion. Incidentally, it is to be noted that the auxiliary plant capacity of the "Queen Mary" amounts to 9 100 kW, whereas that of the "Normandie" is 13 200 kW, or 45 per cent greater.

It is stated in the paper that trawlers are already equipped with electric trawl winches and electric lighting, and it may be inferred that electric propulsion has not yet been applied to this class of ship. The advance of electricity into this field is, of course, seriously handicapped by the present economic plight of the fishing industry, but apart from this I believe there are special difficulties attached to the electrification of trawlers, such as exposure to severe weather, absence of skilled attendance at sea, and the combination of duties in trawling and carrying which demands rather complicated control arrangements. No doubt these difficulties have been or will be overcome, and I would ask the authors whether they are aware of any British trawlers equipped with electric propulsion.

TABLE A.

Name of vessel	Gross tonnage	Propulsion	Auxiliary generators
"Queen Mary"	73 000	Geared turbines, 200 000 h.p. total	7–1 300 kW each
"Normandie"	70 000	4 Turbines, 33 000 kW each 4 Motors, 40 000 h.p. each	6–2 200 kW each

The authors refer in several places to patented systems of protection and control. I suggest that the patent numbers should be given, and also a bibliographical reference to recent important publications within the subject of the paper.

[The authors' reply to this discussion will be found on page 282.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 3RD DECEMBER, 1934.

Mr. William Wilson: The subject of the paper may be divided into three categories, namely, propulsion, auxiliaries, and cables; and I should like to make a few comments upon the first two. To begin with, it seems to me that the value of electric propulsion can be estimated in comparison with direct drive according to five main considerations. The first is space occupied, and I think the authors have shown, especially in some of their lantern slides, that electric propulsion is very definitely superior from this point of view. The second criterion is efficiency, and in this connection I was very pleased to see the set of curves shown on the screen, but for some reason not reproduced in the paper, comparing the efficiency of electric propulsion with geared drive, in which it was evident that the difference may be practically negligible. This is important in view of the reason frequently given against electric propulsion in the Navy, namely that if a warship has to develop its maximum possible speed in order to race an enemy, the losses in the electrical machines will put it at a definite disadvantage. I should like to ask the authors whether they have not shown this argument to be deceptive. The third point is weight, regarding which the authors do not seem to have given us information. It appears to me, however, that the high speed at which it is possible to run the turbo-alternator, combined with the compactness and lightness of the rest of the equipment, should have gone far towards placing the electrical method upon an equality with the mechanical, and I should be interested to have the authors' comments on this point also. The fourth consideration is the short interval required between runs, evidenced in a striking manner by the slide showing the time-table of a typical electric ship, in which the wait at terminal ports was apparently from 2 to 9 hours. This must constitute a vital advantage, and I have been trying to analyse the reason for it. It seems to me that the great improvement introduced by electrical designers as regards the bearings of their rotating machines must have a great deal to do with it. Both turbo-alternators and motors are, as is well known, designed to run continuously, the bearings being self-lubricating and requiring maintenance only at long intervals. If this is the reason for the shortness of the wait at the terminal ports, it is particularly interesting, since the bearings, which undoubtedly constitute the most troublesome element in direct or geared engine propulsion, are a mechanical component which electrical engineers would seem to have improved in a striking manner. Some details as to bearing design would therefore be acceptable. The final consideration is cost, which again has not been mentioned by the authors, probably on account of the difficulty in arriving at a comparison. I should be glad, however, if they could give at any rate an approximate idea of the cost of electric propulsion relative to the older methods. As regards auxiliaries, the descriptions of the authors visualize fully automatic working for practically every item, and I should like to support this policy. Critics of automatic working seem to consider that it is adopted to save operators trouble, or to produce a more " patent " way of doing things; and that while it is in order for small power devices, such as slot machines or telephones, it is quite out of place in high-power engineering. Actually, the opposite is the case, for it will be found that the electric motor has had its application extended to such very difficult situations as the rolling-mill and the ship by virtue of this very type of control. Such strenuous functions have been fulfilled by first enabling the motors to give consistently the maximum output of which they are capable, secondly by safeguarding them so that under no circumstances can they be overstressed, and thirdly by permitting the operator to concentrate his attention upon the work that the machine is doing and to forget about the motor and the control gear. All these are accomplished by automatic control, which will be seen to have played a most important part.

Dr. M. L. Kahn: One of the advantages of using electrical machinery on board ship extensively is the exceedingly low maintenance cost. This experience is at par with similar experience on electrical locomotives, where the maintenance is only a fraction of that of a steam locomotive.

Naval architects have sometimes suggested the application on board ship of the principle of the land powerhouse, i.e. a central generating station with busbars which will serve the whole power and lighting supply, including ship's auxiliaries and hotel load, as well as the propulsion. This idea is in my opinion a misconception, as power stations on land are essentially governed by the condition that they have to supply energy over a considerable area, whilst on board ship the points of consumption are very close to the points of generation. It would be very undesirable to sacrifice the flexibility which is obtainable by separating the supply units for the various requirements, for the sake of a uniformity for which there is no necessity.

This brings me to another question which has recently been considered, namely, whether the present practice of using d.c. motors for ship auxiliaries could be profitably supplanted by the use of a.c. distribution and 3-phase motors. This idea seems to me also to rest on a misconception. The fundamental reason for the change in distribution from d.c. to a.c. supplies has been the fact that alternating current can be transformed to any required voltage by means of a static transformer, whilst this is impossible for direct current. Alternating current is therefore much more suitable for energy transmission and distribution. This consideration is unimportant on board ship, except when on very large liners the total weight of cable required for energy distribution is fairly heavy. I cannot see any real objection to using on such ships a 3-wire power distribution system of 220/440 volts—220 volts for lighting and 440 volts for power. If the neutral is connected to the framework of the ship, there can nowhere be a voltage of more than 220 volts to this framework, which is at par with the present practice. All motors, irrespective of size, can then be arranged for 440-volt working. Alternating-current distribution would presumably be arranged for a somewhat similar voltage, so that this disposes of the cable question. There is only one other point to be considered, and that is the fact that the 3-phase squirrel-cage motor is the most robust and reliable piece of electrical machinery we possess. Direct-current motors, though they embody a commutator and brushgear, can now be made absolutely reliable, so that they can be used for many years with the minimum of attention. As there is always a staff of skilled engineers available on board ship to inspect, and, if necessary, overhaul, the whole equipment, the advantage of the squirrel-cage motor is rather illusory. Speed variation is in most cases required for auxiliary drives on board ship. As is well known, this can be efficiently obtained if a.c. motors are used, but, though it is possible to produce a.c. commutator motors which are quite satisfactory, they can never be quite as simple and reliable as d.c.

motors. On larger units the difficulty can be overcome by using Ward–Leonard control, i.e. converting the a.c. supply to direct current. The booster control referred to on page 245, which results in a much lighter and more efficient solution of this problem, can obviously only be used if a d.c. supply is available. A further point which has an important bearing on the matter is the question of noise. The most penetrating and objectionable noise emanating from electrical machinery is not mechanical in origin, i.e. it is not caused by fans, bearings, or brushgear: it is the high-pitched magnetic hum which has its seat in the teeth and in the gap. Whilst on d.c. motors the magnetic hum can be considerably decreased by using a large gap, this cannot be arranged for on a.c. motors, which are therefore, more particularly during starting, generally more noisy than d.c. motors.

With regard to the selection of motors for propulsion, I believe that, in addition to the advantages in connection with power factor which synchronous motors offer, mechanical considerations have also played an important part in making this type of motor more or less universally adopted in modern ship practice. On very large induction motors the securing of the end winding is always a difficult problem. On the other hand, the field coils of a synchronous motor, which are wound with copper strip on edge, insulated with mica and asbestos, can easily be secured and are almost indestructible.

In connection with the design of alternators (page 250), the requirement of stability is the factor which determines the size of these machines. It must be remembered that they are permanently connected and work in conjunction with motors which take their full output; the power demand of these motors can vary quite rapidly, especially in the event of a sudden reversal of the ship.

Mr. H. W. Richardson: The authors give three principal conditions which marine electrification must meet satisfactorily. The first is the small space available for machinery, the second deals with the need for low maintenance costs, and the third refers to the importance of ease of control. These are three fundamental conditions which all electrical installations have to meet, and in no branch of industry are they better met than on ships.

With reference to the need for economizing engine-room space, it would be of great interest if the authors could give the dimensions of a few typical engine rooms equipped for electrical propulsion machinery, and some details of the plant and apparatus accommodated. Undoubtedly the design and lay-out of the equipment would be found to compare most favourably, from the point of view of compactness, with corresponding land installations.

In view of the competition with other forms of power drives, great importance attaches to the cost of upkeep and repair of marine electrical plant. It would be of value if the authors could provide any figures relating to such costs.

Modern systems of bridge control of electric propulsion equipment provide remarkable ease of control for a vessel, resulting in what may be styled "a high degree of manœuvrability." The results of tests to show times taken to reverse from full speed ahead to full speed astern, for full-speed turning circle, and other trial manœuvres, would make a most useful addition to the paper.

Mr. A. G. Engholm: The authors do not seem to have touched upon one point which affects the comfort of passengers, namely the heating of the cabins, saloons, and other parts of the ship, by means of electricity. Most ships especially those on the North Atlantic service, are equipped with steam heating, but I believe that the "Queen Mary" will be equipped with electric heating in all the cabins. I understand that the main reason for adopting electric heating was that there is such a large amount of electrical gear to be operated that it is necessary to run quite large generators while in port. The "Queen Mary" will be one of the first of the large North Atlantic liners to be equipped with electric heating. Can the authors give any information as regards the cost, per 1 000 sq. ft. of radiating surface, of heating a ship electrically? Undoubtedly there is quite a big future for the electric heating of ships.

Mr. O. W. Minshull: I note that the authors make only a short reference to cables, and I should therefore be glad to know what developments have taken place as a result of the failures originally obtained with lead-covered cables owing to vibration.

I should also like to know the results of their experience with the H.R. type of cable, and whether there are any recorded cases where "Thiokol" sheathed cables have been adopted for special situations.

Although the authors refer briefly to the question of the use of pure rubber next to the copper strand, unfortunately they do not state what the conclusions of the Admiralty are in this connection.

Mr. H. J. Coates: With regard to the question of the control gear of ships, I should like to emphasize that there is little need to provide both electrical and mechanical control. Unfortunately, however, we are in the hands of the surveyors, such as Lloyd's and other insurance companies, who insist on some form of mechanical alternative if electrical control is used. There is certainly no necessity for both, since either can be made a sound mechanical engineering job.

Dr. C. C. Garrard: The flexibility and other incidental advantages of the electric drive have outweighed its inherent loss of efficiency. In the case of passenger liners, greater comfort and freedom from vibration make a ship much more attractive to passengers, and therefore an electric ship will earn more money than a steamship. This consideration is very much more important than is the reduction in fuel costs. On page 241 the authors mention that the total power of electrically-propelled ships exceeds 1 000 000 s.h.p. I take it that this figure excludes warships and refers only to commercial ships. A battleship must be designed for its fighting efficiency, pure and simple; and the incidental advantages which I have mentioned, i.e. greater convenience, comfort, etc., do not apply to battleships. The authors have referred to a cement-carrying vessel which carries 2 300 tons of cement and is self-unloading. The whole of its cargo can be unloaded in 3 hours, by 3 men. This wonderful feat is accomplished by utilizing special scraping machinery which is electrically driven; such a ship would be an economic impossibility unless it were electrically propelled. There are now, I think, two electrically-propelled tugboats in this country. I really believe that the owners of tugboats do not know the advantages which electric propulsion offers in connection with such vessels. The advantages of flexibility and ease of control are tremendous. This question of electric propulsion is not so much a matter for the electrical engineer as for the naval architect, who will have to be converted. Naval architects should at least consider electric propulsion for any ship which they may be designing. I hope, for example, that the sister ship of the "Queen Mary" will be electrically propelled. With regard to the use of air-break switches, for land practice of course we use oil circuit-breakers; but in all the ships illustrated by the authors I believe air-break circuit breakers have been used. The reason is that air-break contacts are very much more durable than oil-break contacts when they are used a large number of times.

The authors show illustrations of certain small vessels which have bridge control. I think that principle should be applied to larger ships, because the most unreliable thing about a power station is the operators.

Mr. J. C. Turnbull: I cannot agree with the authors' comment (page 246) that "wherever possible the electrical equipment of deck auxiliaries should be housed below deck or in deck houses." A deck house can be stove in, and in any case is always in the way. Placing equipment below deck uses room which is intended for other purposes. Winches and windlasses should have built-in watertight motors and automatic contactor starters with fool-proof arrangement, so that the operator can put the handle to "forward" or "reverse" and the motor will pick up automatically. Over 2 000 of these winches are installed in ships of many nations, and no trouble has occurred with them. There is a magnetic brake, a foot brake, and a centrifugal brake to prevent overspeed. "Inching" is easy, so that cargo may be broken out from awkward places in the hold. The controls can be incorporated in one handle if desired, so that the operator can look into the hold while operating the winch. Windlasses and warping capstans are made in the same way. I know of a ship whose engineer took the maker's word that the motors were watertight, and in consequence none of them would work when the ship completed her maiden voyage. Her sister ship had no trouble, as her engineer caulked all joints with red lead when the voyage began. This equipment was made by a firm with little experience of marine work, whereas the winches described are made by a firm having over 50 years of marine experience.

Mr. R. H. Rawll: I notice that according to the paper the auxiliary supply for power and lighting may be of 110 or 220 volts, and possibly 440 volts for power purposes. I quite realize that in marine construction this country has to manufacture for the world's markets, and that consequently in the execution of contracts for other countries a low voltage has to be provided to suit the particular requirements of that country. On the other hand, this country has had quite enough in the past of being saddled with non-standard voltages, and it would therefore be interesting to know whether there is any likelihood of an internationally recognized low voltage being standardized for marine work. I am very interested in the method adopted of utilizing a common starter for the large-size auxiliary motors which are running continuously. It seems to me a simple and at the same time a radically new departure, which I think could be utilized in quite a number of conditions ashore. I can quite see that in a large factory where there are a number of small motors of the same horse-power and characteristics installed the interconnection of wiring rendered necessary by a common starter would be so complicated that it would outweigh any advantage gained, but I certainly think that in many cases, such as large motors driving pumping installations, this principle could be utilized with decided advantage.

Mr. C. V. Peake (*communicated*): A matter of importance to which I should like to refer is the testing of electrical propulsion machinery prior to installation on board ship. By making the necessary preparation beforehand, very much can be done to ensure that rugged reliability which is so essential in machinery at sea. By assembling together the various auxiliaries and components such as fans, exciter sets, coolers, and their housings, etc., one can obtain positive assurance that each piece of apparatus will function adequately and form a reliable link in the chain. Synchronous motors, for example, of 5 000 s.h.p., such as those installed in the "Monarch" and "Queen of Bermuda" respectively, referred to by the authors, can without difficulty be tested by the back-to-back method under full and, even, overload conditions, and at guaranteed power factor, before leaving the manufacturer's works. By providing the necessary adjustment between the half couplings, the electrical angle between the poles of the two magnet wheels can be set to give the desired load and power factor under rated-voltage conditions. Such tests are invaluable to all the parties concerned, and prove in the long run extremely economical. Under such test conditions the shafts are actually transmitting the full horse-power, whilst bearings, lubrication system, conductor insulation, steel laminations, and all other parts, are stressed before installation on the ship to the actual load conditions and working temperatures. The power required for such tests is by no means prohibitive, since it is merely necessary to make up, either mechanically or electrically, the losses in the two machines undergoing test.

Mr. W. Royle (*communicated*): The section of the paper dealing with motor starters and controllers is very interesting to the control engineer, as it indicates the modern tendency to use automatic starting gear on board ship in a manner similar to that in the industrial field. The method by which acceleration of the motor is obtained is also interesting, the oil dashpot, which at one time was so popular, having given way to the various modern mechanical or electro-mechanical timing devices which are free from the variations in timing due to changes in viscosity of the oil with temperature. The authors do not refer to the use of air dashpots, mercury switches, or bimetallic thermal strips, as means of obtaining a time delay in connection with the starting of small motors. I should like to know their experience in the matter. The use of the back e.m.f. of the armature of small motors to close an accelerating contactor appears to be as simple and cheap a method as one could wish; and, provided that a pilot lamp is used which can only light up when the machine is running and the accelerating contactor is closed, this seems to get over the disadvantages mentioned by the authors.

Many engineers now apply the timing device to schemes where current control was once popular, one advantage, in addition to those mentioned by the authors, being the reduction of the magnitude of the starting peaks, i.e. the time relay allows the starting peaks to fall to a minimum, whereas the current relay or current lockout must be set to cover the greatest valley figure the motor is likely to experience during starting, on its particular service.

[The authors' reply to this discussion will be found on page 282.]

North-Western Centre, at Manchester, 4th December, 1934.

Mr. G. F. Sills: May I ask why alternating current should not be considered for distribution purposes? I happen to know one ship so equipped which has been perfectly satisfactory. Apart from the main propulsion motors, a considerable number of motors on a ship and equipment could be just as satisfactorily operated with alternating current as with direct current. In view of some advantages which could be obtained it does not really complicate matters to have both a.c. and d.c. supplies on a vessel.

I should like to stress a particular feature which should be included in all ships, namely, high rupturing-capacity fuses of the non-explosive and non-deteriorating type. I believe these have been standardized on tankers by more than one nation to minimize the danger of fire from fuses; if this is good practice on a tanker, surely it is still more important where perhaps 3 000 people are on a ship. On a large ship there are literally thousands of fuses, each one of which is a potential source of fire, and after what has happened in the last few years it would be of interest to know why the practice of using the ordinary type of wired fuse is persisted in. The increase in the cost of a ship which the change would involve would be absolutely negligible.

It is interesting to record that a Diesel-electric paddle boat has just been ordered, 215 ft. long, having a speed of 17 knots. The drive to the paddles is to be direct electric, without the intervention of gears and chains. The double-armature motor, which enables a low overall height to be obtained, is directly placed on the main shaft, and the interesting feature is that both paddles are on the same shaft. This is a departure from normal practice, and shows that the electric drive is still making progress.

Mr. G. A. Juhlin: The authors describe at some length the system of drive for various purposes on board ship, but give no comparative data of cost, weight, and fuel consumption, the points which are brought up in comparison between the electrically-propelled ship and the steam-driven ship.

The authors emphasize certain conditions, such as that the generators may have to run in a fume-laden or oil-vapour-laden atmosphere. These conditions, however, are not peculiar to ship installations, but are met with to the same extent in Diesel-driven stations.

The frequency adopted for the drive described in the paper is 50 cycles per sec. It may be of interest to state that the frequency adopted for the propulsion machinery on the new French Atlantic liner is 80 cycles per sec. The advantage of the high frequency is, of course, very marked in connection with the weight both of the generators and of the propelling motors.

In dealing with the systems of propulsion, the authors appear to have almost ignored one system which has proved extremely satisfactory in practice. There has been in recent years a considerable amount of reconstruction of merchant tonnage, and in many cases it has been found desirable to increase the speed of the vessel, or in some cases to improve the consumption. This has been accomplished by providing a turbine receiving the exhaust steam from a reciprocating engine. A d.c. generator is coupled to the turbine through gearing, and a d.c. motor is introduced in the propeller shafting to absorb the power provided by the steam turbine. We have equipped altogether 13 vessels with machinery of this description. Some new vessels have been built, but the majority of the equipment has been installed for reconstruction purposes. The results have proved very satisfactory, and the scheme has some very definite advantages; it compares well with the Bauer Wach drive.

In considering the drive to be adopted, it is, as the authors say, essential to give due consideration to the class of service for which the vessel is intended. From the point of view of manœuvrability there is no doubt that direct current has a very distinct advantage, as there is no difficulty in reversing the propeller in 2 to 3 sec., which time is frequently obtained in rolling-mill practice. The direct-current system lends itself very readily to bridge control, and in this connection it may be of interest to state that the company with which I am associated was responsible for the first twin-screw Diesel-electric-driven vessel built in this country. This vessel, which was double-ended, was designed for a ferry service in South America, and was provided with three control stations, two on the bridges and one in the engine room. Two other types of vessels, each of which was the first of its kind, were a fast passenger twin-screw vessel for the Western Isles service and two paddle-driven ferry boats for the Firth of Forth. In both types the direct-current system was adopted; the former was fitted with bridge control, and in the latter type each paddle was driven independently by a d.c. motor by means of chains to the paddle-wheel shaft. A separate Diesel set was provided for each paddle wheel, fully independent control being thus obtained. These ferry boats have been in use for some time and have proved very successful.

I am interested to note, from the drawings reproduced in the paper, the adoption of disc-lubricated bearings. We have used this type of bearing now for some 8 years and have found it very satisfactory. It has a decided advantage in that it enables one to dispense both with oil rings and with lubricating pumps; the latter are an added complication.

Mr. D. B. Hoseason: The authors have adopted the natural course and divided their subject into the two categories of the ship's services and the main propulsion machinery. I do not think there can be very much doubt about the efficiency and success of electric drive in the general services, since on land electricity has become supreme in regard to these. The situation of main propulsion, however, is not so clearly defined. In many respects it corresponds to main-line railway traction, with this important difference, that the generating plant is invariably carried along with the ship and the case therefore corresponds to the turbo-electric or the Diesel-electric locomotive. Neither of these two propositions have made much progress for long-distance main-line working, except where water shortage or other similar features have existed. To me, it does not appear to be fundamentally economic to introduce the additional energy conversion by the use of electricity, unless we wish to obtain some special feature for which efficiency sacrifices should be made. The only feature which I think can justify efficiency sacrifices is manœuvring ability: hence the expansion or more favourable consideration of electric propulsion in war vessels and tugs, and the failure to get a firm hold on the straightforward fast traffic such as that on the North Atlantic.

The authors advocate the use of ball and roller bearings wherever possible. I hope marine engineers will hearken to this, because the ball or roller bearing is not as popular as it should be for marine service.

The authors refer briefly to condensation. I should have liked them to have dealt more fully with this subject, because it is a very serious problem in the design of marine machinery. The paper states that varying temperatures introduce the risk of condensation inside the machines, and breathing must be provided for. I suggest, however, that breathing will not stop condensation; in fact, it will only allow more damp air to come in and go out than before, and condensation, if anything, will be rather more serious. It is, however, necessary to provide breathers, particularly with roller-bearing machines, to prevent the breathing taking place through the bearing glands, and possibly sucking some of the grease into the machine or in certain cases drawing dust into the bearings.

I should like to ask whether the authors have considered the use of any special device to deal with condensation inside totally-enclosed machines, other than the heaters on very large plant. It is quite common, unfortunately, to obtain as much as half a cup full of water at the end of a week or a fortnight from a motor 2 ft. or 3 ft. in diameter, which is undoubtedly a serious matter. Ship builders use powdered-cork paint with the object of reducing condensation inside their vessels. Have the authors attempted painting with powdered cork the insides of their machines, and, if so, with what result? May it not be desirable to allow the condensation to take place on the metal parts, and thus not on windings and the vulnerable parts of the apparatus?

The authors state that all machines for marine service should be specially impregnated to withstand tropical conditions; have they any new form of impregnation which we ought to know about? Bitumen can be used for stationary portions of machines, but cannot be used on rotating parts because it flows out under the centrifugal force. If we impregnate with varnish, which has a solvent to be driven off in the course of drying out, the solvent from the inner parts comes through and punctures the varnish skin, which hardens in the early drying stages.

Mr. R. M. L. Evans: With regard to the plural starting control (Fig. 1), I take it that the motor-operated starting-rheostat drum is continuously rotating in one direction; there appears to be no means of returning it to the " off " position. It is not clear how the authors prevent two or more motors starting up at the same time if the " start " buttons are pressed simultaneously. Also, it is not clear that would happen if one motor is in process of being started and another motor " start " button is depressed; how is the second motor prevented from putting itself on to the starting busbars? I should be glad of further information as to the essential tripping busbars; these are apparently connected to the shunt trip coils on some of the circuit breakers.

I am sorry the authors do not give more space to individual starters, because I suppose for every plural starter there are thousands of individual small starters, consisting of a single- or double-pole line contactor with a drum-type starting rheostat. If a single-pole line contactor is used it is connected in the positive line, and the starting rheostat in the negative line. A magnetic overload relay is usually provided, and, if required for a variable-speed motor, a shunt field rheostat. " Running " or " alive " lamps complete with fuses are available if required. In the design of such starters there are a lot of points—compactness, accessibility, and proof against shock, vibration, list, and rough handling—which are not brought out in the paper.

The authors stress d.c. bridge control, but I cannot see why there should not be equal opportunities of obtaining bridge control with a.c. propulsion in the same way as with the Diesel d.c. scheme. Remote control of the main turbine stop-valve could surely be obtained, by an oil servo system or electric follow-up device, from the ordinary ship's telegraph control. The problem would appear to present no great difficulties that have not already been overcome in connection with the d.c. scheme.

Mr. D. A. Trickett: In the section dealing with motor design (page 248) the authors outlined the main features to be observed when dealing with silent machines for ship work. I have found that the number of slots employed on the motor armatures is almost as decisive as the factors they mention. I can also confirm that it is possible so to modify the magnetic hum as to make it imperceptible; the commutator noise is then practically the only one that is noticeable, and at low speeds that also is negligible. It would appear that the precautions which produce silent running also result in immunity from wireless interference.

It is an interesting problem to find a way of effectively excluding driven moisture, due to a severe gale, from a deck machine, using doors which are reasonably free for access. Experience shows that some form of machined face is practically essential. That face can be well greased or provided with suitable packing, and, what is equally important, designed with a sufficient number of bolts. Even so, provision should be made for faulty maintenance; by that I mean that if the maintenance staff fail to secure the doors properly, or if during the building of the ship the doors are removed and improperly replaced, any water that gains access to the machine should be able to find a path away without causing any damage. I know of a case some years ago where the lack of a small hole at the lowest point in the frame resulted in considerable trouble.

In connection with the machines of which I have had experience I do not think condensation inside the frame has caused any great trouble, but I do remember an instance some years ago where condensation within the windings themselves was a difficulty. When that case was investigated it was found that the field coils which were the source of difficulty had been insulated with mica. The mica was actually in contact with the cotton covering of the wires. The usual process of drying *in vacuo* and impregnating under pressure had been followed, and yet breakdowns occurred in a very mysterious way. The investigation of this throws an interesting light on the circumstances under which condensation occurs and how it can be avoided. Picture a cold mica surface, a machine starting up, and a small amount of retained moisture in the coil. The last atom of moisture is never driven from the cotton; the retained moisture is liberated internally as the winding warms up. The mica walls, particularly those in contact with the cold frame, are cold and allow condensation to take place, and that free moisture is a source of danger. If instead of a mica wall there is a separator of leatheroid, or some similar substance, between the mica and the cotton, the condensation of free drops of water is prevented, and consequently coils insulated in that way are perfectly safe. The theory is the same for the marine engineer's cork paint, and I have heard that switch makers are now using cork paint inside their switch cubicles and switch cases to prevent condensation. The important point is that under correct conditions condensation can be kept safely under control.

The all-a.c. ship is not yet a practical proposition, because of the comparatively large units where a wide range of speed control is necessary. For example, the marine-winch engineer expects to have the same control with an electrically-driven winch as a stevedore can have with a steam stop-valve, varying the speed from dead slow and up to the maximum. The methods of doing this with direct current, referred to by the authors, are entirely successful. A minor correction is needed in connection with the series system of operating winches, where the authors mention that the machines have to carry full current continuously whether they are in use or not. It is only the generators and cables that have to carry the full current continuously, because the controllers for the individual motors can short-circuit them when in the "off" position.

Mr. H. Cobden Turner: I am disappointed that the authors do not say anything about the question of cost. It seems to me important that we should know whether putting electricity on board a ship in the way they have done, has reduced the cost of the boat: and whether there is any possibility on that account of the practice of installing electrical drives becoming more widespread.

Does the electrical engineer on a boat still rank just as an electrician? On a vessel like the "Monarch of Bermuda" the chief engineer and the second engineer are presumably steam engineers. Is the electrical engineer, who must have 90 per cent of the operating machinery under his charge, still merely the electrician, or does he become the chief electrical engineer?

Mr. R. Johnson (*communicated*): I propose to limit my remarks to four points in connection with electrical auxiliaries on board ship.

Firstly, in the Introduction the authors state that to-day almost all auxiliary machinery is, in most important ships, electrically operated. This is certainly the case in connection with passenger vessels, but it does not yet, unfortunately, apply in the case of the majority of cargo vessels. The steam winch, for instance, holds its own very effectively in this field. Its price is little more than one-third that of the electric winch, and capital cost—particularly at the present time—is regarded as of primary importance. Further, in spite of the fact that on certain ships it has been found that electric winches would show a fuel consumption as low as one-sixth that of the steam winches installed, it is not a simple matter to demonstrate to an owner, or his superintendent engineer, that the extra first cost is returned in full measure owing to the higher efficiency of the electric winch.

Secondly, on page 244 under the heading "Auxiliary Supply" the authors state that "alternating current has in a few cases been tried." It may be of interest to recall that one prominent electrical company 10 or more years ago equipped some 25 tankers with a.c. motors throughout, and that these proved an unqualified success. Alternating-current motors were applicable in this case as the majority of the applications were constant-speed drives. On passenger and cargo ships, however, a considerable number of drives demand variable-speed motors, and in such cases d.c. machines are of course preferable. Schemes have been worked out under which the main supply should be alternating current, with convertors to give direct current for windlasses, winches, etc. Although such schemes show certain advantages, they have not yet been adopted in any ship.

Thirdly, on page 248 under the heading "Motor Design" the authors state that ball and roller bearings are being used in increasing numbers. I think that this statement should have been amplified. The position at the present time is that the superintendent engineers of the principal shipping lines are generally antagonistic to such bearings. This criticism has some foundation, seeing that early motors mounted with ball or roller bearings in many cases gave trouble due to bad fitting of the races allowing movement to take place, with resultant ultimate failure. Such trouble, of course, is practically unknown nowadays in the products of responsible electrical manufacturing concerns, but memories are long in such matters. Apart from this, however, ball- and roller-bearing machines cannot be recommended for a number of applications on board ship. Motor-driven engine-room auxiliaries may be situated where heavy vibration occurs, and in such cases the sleeve journal bearing is to be preferred. In cases of this kind, ball or roller bearings may be ruined before the motor has been working for any length of time, owing to the pounding action of the balls or rollers on the races during periods when the motor is stationary. Such cases have occurred in naval craft—submarines and destroyers—where vibration has been very bad. Cases have also been known on mercantile ships. For motors driving fans in connection with the ventilation of cabins in liners, ball and roller bearings are also unsuitable as such bearings give sufficient noise to be a nuisance.

Fourthly, in connection with the question of noise and the need for super-silent machines for certain applications (page 248), I do not feel that the authors have given the position quite correctly. They state that the magnetic hum in motors " can by suitable design be reduced to a minimum." It is a fact that the magnetic hum in d.c. machines can be entirely eliminated, leaving only the faint noise due to the rubbing of the brushes on the commutator. Such machines are regularly being supplied for use in connection with the ventilation systems of liners.

[The authors' reply to this discussion will be found on page 282.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 10TH DECEMBER, 1934.

Mr. G. G. Mallinson: Broad principles are not at issue when electrical gear is used on ships. Details make the difference between success and failure, even to the extent mentioned by the authors of using a special impregnation for windings to resist the brine-laden atmosphere. It seems certain that developments due to the late Mr. Wordingham at the Admiralty have done much towards the satisfactory operation of electrical gear at sea. Marine electrical engineers owe a good deal to this pioneer.

On page 248 the authors describe a plural starter. Will they give their opinion of this method after sea-going experience? I am under the impression that one firm of shipowners discarded a control system of this type after sea experience on one or two ships.

The safety of ships at sea undoubtedly calls for great care in the selection of the proper type and size of cable. Considerable thought must be given to design and installation. Cables should be of ample size to avoid undue internal heating, and should be suitably protected externally to act as a fire resister and prevent fire spreading along the cable run.

During the mad rush to complete the fitting-out, plumbers, painters, platers, and electricians, tumble over each other, and often cables are damaged. Very often this damage is not enough to show on test, but trouble develops later on. In a luxury stateroom with a multitude of switches neatly grouped together, the jamming of ends of cable together in a last-minute rush does lead to trouble. I suggest this could be overcome by making the switches up in a unit, and permanently connecting to substantial side terminals. A neat job can then be made of the wiring: it is easy to install and maintain. Naval architects now make an effort to allow for main cable runs, whereas in the past it was sometimes almost impossible to make suitable arrangements to accommodate the cable runs.

The authors state that electricity has taken a long time to become established on board ship. This is largely due to the conservatism of those who go down to the sea in ships. They are rightly conservative—safety of life is their consideration. Gear must be reliable, because on board ship no workshop facilities exist. The makers' works are not available, and in the event of breakdown of gear it is sometimes impossible to find out the sequence of events leading up to it.

With the extending use of electrical gear may we hope that the Board of Trade will grant certificates to duly qualified electrical engineers, and thus attract the right type of man?

Mr. W. H. Pomeroy: I am interested to note the authors' remarks regarding the necessity of planning the installation: this matter is of great importance, particularly in connection with main runs along passages and other places where panelling is fitted to conceal the wiring. In recent years there have been some very serious fire disasters, and when a fire occurs the electrical installation, even though it may be in perfect condition, can hardly escape suspicion. The popular idea nowadays seems to be that every fire of any magnitude is electrical in origin. All those engaged in the task of fitting electrical installations in ships bear a large responsibility to their fellow men. A fire starting behind panelling two or three decks down is about the worst situation one can be faced with. The area becomes unapproachable in a few minutes, and the fire quickly spreads until the whole ship is involved. Owners and builders should insist on planning of the installation, and also carefully inspect all work before it is covered up. If the electrical installation in congested places is planned, all other work must also be planned, and it is usually found that the money spent on this work is more than repaid owing to the facility with which the work can be carried out. The latest types of hard-rubber-insulated lead-alloy-sheathed and fireproof braided cables on porcelain or lignum-vitæ racks are very satisfactory for main runs where space is available. In restricted spaces, however, the racks must be abandoned and the cables clipped to light plating in the ordinary way. Long, straight runs should be avoided, as the working of the ship may put a great strain on cables so fitted; horizontal or vertical deviations can usually be worked into the run.

Mr. C. Turnbull: The problem of accessibility of machinery at sea is a very important one, and it does not receive the amount of attention it deserves. The Peninsular and Oriental Steam Navigation Co. have two recent turbo-electric ships: is the third one, now building, to be turbo-electric?

When I inspected the " Monarch of Bermuda " I was greatly struck by the simplicity of the arrangements. The position of the turbines made the steam pipes short and simple. The condenser arrangement was also excellent, owing to the fact that it was not necessary to place the turbines in a position which fitted the propeller shafting. These advantages are all to the benefit of the turbo-electric drive.

Mr. A. Oliver: On page 253 details are given of two separate circling trials held on the "Monarch of Bermuda." I presume that in both the cases mentioned the ship was running at the same speed, also that all the propellers were running ahead and the steering was by helm only. This being so, the percentage shaft horse-powers of each motor from port to starboard are given as follows: Case (*a*), 32, 16·5, 28·5, 23. Case (*b*), 27, 17, 34, 22. How is it that in (*a*) the greatest load is on the outer port propeller? I should have expected this to be on the starboard side, as in a twin-screw vessel. It is also remarkable in (*b*) that the inner starboard shaft takes the greatest load. Comparing the two cases, why is it that after a change-over in connections between the alternators and motors there is a difference in the power taken by each shaft. Is this due to a change in power factor or excitation? Another interesting point is that in both cases the motors running anti-clockwise are taking more load than those running clockwise. Is this a coincidence, or is it to be expected when changing course with a quadruple-screw vessel?

My final point refers to page 254, col. 2, where reference is made to switching at $\frac{1}{5}$ speed. Was this chosen for a theoretical reason, or was it simply a question of convenience in design?

Mr. W. F. Smith: In passing from the geared turbine to electric propulsion the gears are replaced by motors and generators, which would seem to result in a considerably increased capital cost. The question of costs is not referred to by the authors, and I should be glad to know whether this aspect is responsible for the slow development in electric propulsion of ships. It is hardly likely that the advantage of easy control would outweigh the disadvantage of increased capital charges, except perhaps in connection with the largest liners, where, in addition, cleanliness is an important factor.

The marine engineer has had some difficult problems to solve in connection with the electrical propulsion of ships, but in connection with the control of auxiliary plant he has facilities which are not available to his land colleague. The whole of the plant is under control from the engine room, and the ingenious method of controlling the various circuits according to their relative importance on the occurrence of an overload is unique. The power-station engineer would welcome the opportunity to be able to apply such a scheme to his network. I am particularly interested in the plural starting of motors; this again could have only a very limited application on land.

The development on land has been towards the more general use of alternating current; a.c. machines can now be constructed for almost any duty. Why has direct current been employed to such a large extent for the auxiliaries on board ship? Control of a.c. machines is almost as easy nowadays as that of d.c. machines.

Mr. N. H. Denholm: The vessels listed in Table 1 are all passenger liners intended for cruising work, for which the turbo-electric drive offers distinct economies. The "Monarch of Bermuda," in particular, as her sailing schedule shows, has a very high proportion of manœuvring time to open-sea time. The electric drive offers obvious advantages in flexibility of control, ease of reversal, and economy of running.

In the case of vessels which are to be used for purely transatlantic service, however, the advantages become negligible compared with the cost and complexity of the electric gear, as the manœuvring time is a relatively small proportion of their running schedule. In addition, the transatlantic vessel runs the majority of its sea time at full speed, so that the economical cruising speeds of the electric drive are at a discount, and the system is a needless complexity.

My final point is in connection with deck auxiliaries, the supply for which is at present almost universally direct current. Apart from the question of cost, it is surely possible to design a.c. drives which will give the necessary torque and stalling characteristics, though their use might increase the necessary overload capacity of the auxiliary generators.

Mr. R. J. H. Beaty: Referring to the synchronous motor shown in Fig. 5, I should like to ask the authors the maximum torque exerted by this machine when run as an induction motor with double excitation on the alternator.

On page 234 (col. 2) it is stated: "Since the voltage is also low, owing to the low speed, the starting-current peaks are kept down to a minimum value." I should expect this current to be almost independent of the speed and nearly proportional to the alternator field strength, owing to the impedance being largely composed of reactance. The interesting feature is that it has been found possible to do the work with salient-pole motors instead of using the more expensive cylindrical rotors which were at one time considered to be necessary.

The torque characteristics of steam turbines and Diesel engines show why a.c. transmission is suitable for the former and d.c. desirable—and in some cases necessary—for the latter. The authors state that for a certain range the use of Diesel engines with alternators and synchronous motors may have possibilities. Would there be a limited field for low-frequency alternators and induction motors?

In regard to the auxiliary power required on a ship, there are so many drives for which direct current is decidedly more suitable than alternating current that the use of the latter can only be justified on a ship which is large enough to have both systems, and then I think it will be best to begin with the hotel load. I suggest that alternating current at not more than 1 000 volts might be run to the galley and transformed down to a very low voltage at the heating elements.

Mr. W. Cross: Referring to page 244, col. 2, am I correct in supposing that, with this special tripping system on the control gear, when the main generator circuit-breakers are tripping no light whatever is left on the ship? It appears to me that this paragraph might be amplified to show that in this case the emergency generator can be automatically started, giving extra security, if such is the case. I should also like to know whether the authors suggest that a battery is preferable to the emergency generator for the emergency lighting.

The shipbuilding industry is in my opinion very fortunate in that the electrical installations are carried out to specific regulations, and more particularly that these regulations are enforced by competent inspectors. That is possibly the reason why we have had fewer fires on British ships than on ships under other control.

The authors' slides show that in many cases it is possible accidentally to touch live metal. Open-type switchboards, though not allowed on land, have always been permitted on ships, despite the risk of shocks which they involve.

Mr. C. E. Clouston: It is disappointing to find that so little space is devoted in the paper to electrical deck auxiliaries, particularly in view of the highly specialized nature of these machines. Modern deck auxiliaries are the outcome of a great deal of experience and development work, and it is safe to say that if they had not reached their present state of reliability no marine superintendent would have given the electrically-propelled ship a moment's thought.

The authors' remarks on booster control (page 245) are rather misleading. It is stated that "on this system the motor-generator has only to develop a small voltage at full load and less than the line voltage at light loads." Farther on, the authors state that "the outfit consists of the main windlass or capstan motor supplied with current from the ship's auxiliary supply, and in series with the motor armature is the armature of the generator of a reversible booster set. . . . The main motor can therefore be supplied with a voltage which can be controlled from zero to double the line voltage." If it is assumed that the line voltage is 220 volts, then, in order that the main motor may be supplied with a voltage of double the line voltage, the booster generator must be capable of developing 220 volts; and since the main-motor voltage is to be controlled from zero to 440 volts, the booster must be capable of supplying 220 volts either to oppose or to assist the line voltage. It is therefore obvious that the first statement quoted from the paper is not correct, since the motor-generator has to be capable of developing full line voltage on the last control step in a direction assisting the line voltage, and almost full line voltage on the first control step in a direction opposing the line voltage. Between these steps the motor-generator set has to develop less than line voltage, the separately-excited shunt field of the booster generator being first weakened, then completely opened, and then built up in the opposite direction to full strength; the shunt field of the main motor being successively weakened at the same time.

The only occasion when the motor-generator set develops less than line voltage on the last step is when an overload occurs. A protective series winding is fitted in the booster generator and arranged to cause the booster voltage to oppose the line voltage; at normal loads the field set up by this winding is wiped out by the separately-excited shunt field of the machine, but on the occurrence of an overload the heavy current which flows through the series winding causes an increase in its field strength with a consequent decrease in the net field strength of the machine and a resulting drop in voltage. In the case of a very heavy overload the protective series field may take complete charge of the booster generator and cause it to develop a voltage opposing the line voltage. Thus it is possible to stall the windlass or capstan quite safely for long periods and maintain a steady, live pull without dangerous overheating.

[The authors' reply to this discussion will be found on page 282.]

SCOTTISH CENTRE,* AT GLASGOW, 8TH JANUARY, 1935.

Lieut.-Commander E. D. Hobson: The majority of the services in a ship are now carried out by centrifugal pumps, either self-priming or non-self-priming, and that type of pump is generally regarded as the one unit which can run at constant speed because it cannot develop excessive pressure and because the pump is practically self-regulating. Economy and first cost being the great essentials nowadays, shipowners and shipbuilders are endeavouring to carry out as many pumping services with each individual unit as possible. For instance, the duties of sanitary and fire service are frequently carried out by the same unit. These duties entail widely differing pumping heads, and consequently pump rotational speeds, in the orthodox centrifugal pump. The quantity delivered at good efficiency by this type of pump varies approximately directly as the speed of rotation, the total pumping head as the square of the speed, and the power absorbed as the cube of the speed. Even this difficulty has been got over by a special arrangement for connecting in series and parallel the impellers in the same casing. There are, however, other difficulties. One is the difficulty of estimating the actual pumping head of each pump service before the ship is constructed, in consequence of which it is quite easy to be 20 or 30 per cent out in the assessment of total pumping head. In addition, one has to contend with the very wide range of output required for cooling water between home waters and the tropics. If the centrifugal pump is to be run at constant speed one must be prepared to face a certain amount of inefficiency and loss of power, or loss of output, if the head does not coincide with the actual working conditions. Shipowners and shipbuilders utilizing constant-speed a.c. motors will therefore have to group their pumping duties somewhat differently and estimate the actual working conditions very much more carefully than is necessary at present, employing the pumps as far as possible, if they are to do two duties, so as to deliver a large quantity at one particular head for one service and a reduced quantity for another service at a higher head, when either series-parallel pumps may be applied or full use made of the inherent characteristics of the centrifugal pump. Otherwise, in cooling-water pumps especially, it will be necessary to have a good margin to allow for frictional losses in excess of the estimate, and to face the possibility of a good deal of excess power consumption and inefficient running owing to the necessity to throttle the delivery to obtain output control, coupled with very considerable wear and tear on the pumps. The latter may be overcome by suitable selection of materials, but these materials are much more expensive, and by the time one has substituted these more expensive pumps there will be little or no gain—at least in initial cost—by utilizing the less expensive squirrel-cage motors and a.c. starters. The modern variable-speed d.c. controllers are made up of mass-produced components and can be constructed very economically, while they are very reliable and simple.

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* At a joint meeting with the Institution of Engineers and Shipbuilders.

Mr. R. J. Butler: The authors emphasize the fact that, in turbo-electric ships, headroom is extremely restricted; from drawings and inspection of some of these ships I find that a considerable amount of space is taken up by the ventilating trunking to the generators and motors. Has the question been seriously considered of eliminating air cooling entirely, and substituting water cooling? By this is meant the provision of water jackets on the stators (like the jackets around Diesel-engine cylinders) and of passages through the centres of the rotors as conduits for the cooling medium. It should not be impossible to provide such a system which would be absolutely free from the danger of water leaking and obtaining access to electrical portions. Besides eliminating cumbersome air trunking and air-cooling plant, such a system would have the advantage that any accidental fire would not be assisted by a forced current of air—small though the quantity in the circuit be.

If, however, there are vital reasons against this method, is there any reason why the heated air from the generators should not be taken to the boilers for combustion purposes, the cooling plant thereby eliminated, and the size of the air preheaters reduced? This was done in a small pioneer vessel—the " Wulsty Castle "—with which I was associated. It is, of course, appreciated that in large installations of two boiler rooms, each containing possibly four boilers, the trunking for this purpose would be extremely cumbersome, but in these days of a few large units arranged in a single room it would not appear to be objectionable, particularly as the generators are arranged fairly high in the ship to accommodate underslung condensers. The trunking could be led above the strength deck.

With regard to Table 1, from the capacities of the motors given it would appear that the motor and transmission efficiency is 98 per cent in the first two ships and 95 per cent in the second two. Mr. Belsey* gave the figure of 97·49 per cent for the " Viceroy of India"; it would be interesting to know how the later ships secure an improvement of 3 per cent.

The authors mention the question of the use of alternating-current motors for auxiliary purposes; I should like to know the views of the makers of pumps and auxiliaries on this subject, particularly in connection with the use of Vulcan-type hydraulic clutches for obtaining speed variation from a constant-speed a.c. motor, such as have been used in a number of instances in power-station work, especially on fan and feed-pump drives.

Mr. J. F. Nielson: With regard to the disastrous fires that have recently taken place on board ship, causing the man in the street to look askance upon the electrical equipment, I think we can compliment ourselves upon the fact that all these fires have occurred on foreign-built ships. Unfortunately, in most cases any evidence that may have existed as to the origin of the fires has been destroyed in the conflagration, and there is the tendency to attribute the outbreaks in every case to the electrical installation, despite the fact that there are many other fire hazards on board ship which might just as easily have caused the outbreaks. Lloyd's and other registration societies, and also the Institution, are fully alive to the question of the prevention of fire on board ship, and their considered opinion is that where ships have been equipped in strict compliance with the regulations issued by these particular bodies the fire risk from electrical causes is almost negligible. Of the few fires that have occurred on British ships which have been reported, it is understood that a number are attributable to injudicious use of electrical equipment, more particularly portable appliances in cabins, such as curling tongs and heaters, which can be easily upset, and not to defective wiring or equipment.

I think the authors have very rightly emphasized the importance of greater consideration being given to the question of cable ducts and routes than has been the case in the past. In my early experiences of electric wiring on board ship we were left to push the cables through in any way possible, but nowadays consideration is given to the fact that adequate provision must be made for cable ducts and for the proper design of routes. More especially is this the case in respect of adequate provision being made for the accommodation of, and access to, the electrical wiring in public rooms and passenger cabins, where the facilities for pushing the electric cables out of sight often tempt the architect to leave wholly inadequate space for their accommodation. If the regulations are conscientiously adhered to, particularly in respect of the routes to be taken by the cables, their proper separation from each other where required by these regulations, and the avoidance of all situations which are liable to be flooded or where pipe joints are liable to leak, and if the cables used are of a suitable quality and are adequately protected from damage, then I think the authors' claim that the life of the cables should equal the life of the ship is probably justifiable.

At the present time the electrical contractor is faced with the difficulty of having to choose from very many existing types of cable, all of excellent quality, the best for his purpose. It is becoming recognized to-day that, in view of the comparatively low voltages on board ship, high insulation, which means the use of pure rubber, is unnecessary, and that a composite rubber insulation, which has a much longer life under the changing temperature and surrounding air met with on board ship, has much to recommend its use. The thanks of the industry are due to the research and experimental work carried out by the Admiralty and the Cable Makers' Association within recent years, in consequence of which many scientific improvements have been made in insulating materials and in the metal coverings of ship-wiring cables. An enormous improvement has certainly been observed during the past 10 years in the quality and reliability of such cables. With regard to the electrical staff on board ship, I think that until shipowners realize the need for an adequate personnel we should fight shy of many of those ingenious devices which work admirably under ideal conditions on land but which become a source of worry and trouble to the few electricians who have to look after them on board ship.

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* *Transactions of the Institution of Naval Architects*, 1930, vol. 72, p. 54.

Mr. J. B. McNee: Referring to Part 2, the authors are quite right in stressing the importance of having the switchboard arranged so that the essential services are maintained down to the last minute. It is important that the operating engineer should receive warning of approaching trouble. On one Diesel-engined vessel which had electrically-operated auxiliaries a sudden failure of the auxiliary generating set plunged the engine room in darkness and stopped all the essential auxiliaries. The engineers on watch were confronted with a very serious difficulty without the slightest warning. The main engines had to be stopped instantly, before the effects of having no lubricating oil or jacket water made themselves felt, and the ship was helpless until another generator could be put under way. Automatic relays, as well as battery-operated police lights, are without doubt essential fittings.

It is difficult for Diesel engineers to comprehend the statements on page 255 to the effect that Diesel-electric control is far superior to direct Diesel drive, and that "A further invaluable advantage is found in the fact that the engines run in one direction only at constant speed and are not subject to frequent starting and stopping when manœuvring is being carried out." The method of manœuvring will seem difficult or simple according to one's training, and while to electrical engineers the method employed for reversing the direct Diesel drive may seem complicated, it really is not so. In the Diesel-electric installation, starting air appliances have to be fitted for the initial start of the Diesel motor; a very little complication is therefore added in augmenting them to serve for manœuvring. Incidentally, it is difficult to see where the direct Diesel drive is at a disadvantage in regard to starting and stopping, since in the Diesel-electric ship this disadvantage has simply been transferred to the main motor.

The two most important factors—efficiency and cost—on which the future of electric marine propulsion will depend are merely mentioned by the authors. Marine engineers would place these two factors next in importance to reliability. While electrical machinery has proved itself thoroughly reliable, the additional incorporation of a generator and motor in the chain of driving units must detract from its reliability.

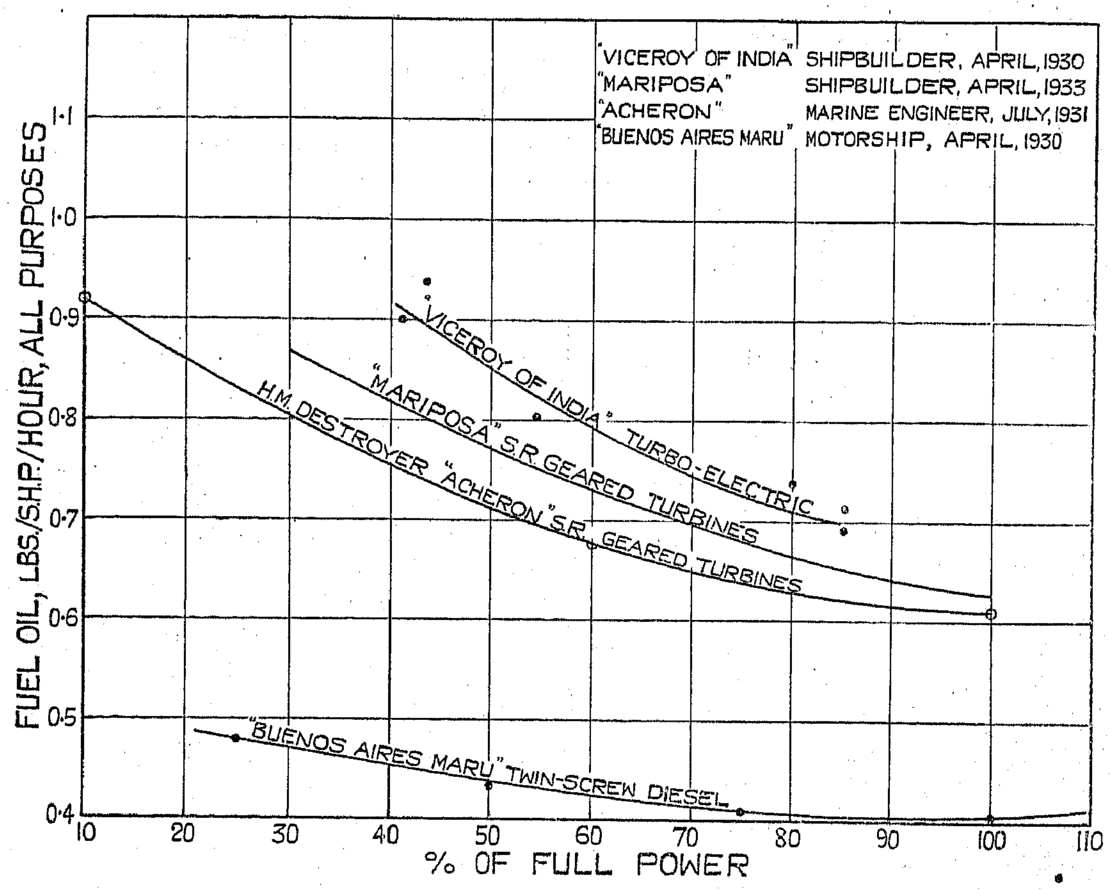

FIG. A.—Oil-fuel consumption of various types of machinery.

It is difficult to see what advantage the electrically propelled vessel has over its most serious rival, the geared-turbine ship, but that of silence.

Some of the vessels mentioned by the authors carry mails. Between certain ports a high speed and a reserve of speed become necessary; between other ports speed is of secondary importance. Such vessels require a steady efficiency over a wide range of power, and there is a general impression that electric propulsion enables this to be accomplished. If the published results of the "Viceroy of India," as given by Mr. Belsey,[*] are compared by plotting the fuel per b.h.p.-hour for all purposes with those for the geared-turbine vessels "Acheron," "Mariposa," or "Monterey" (see Fig. A), it will be seen that the latter vessel easily excels at all percentages of the designed power. There is also a wealth of data relating to other high-class modern vessels that do show a 10 per cent fuel saving at full power over the best figure of 0·691 lb. of oil per s.h.p.-hour quoted by Mr. Belsey.

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[*] *Loc. cit.*

I do not think the fuel consumptions over a range of power for the Diesel-electric drive have been published. Under normal conditions the Diesel engine has the most constant efficiency of all marine units, and it is possible that the addition of the direct-current motor and generator will cause a much more rapid falling-off in efficiency. As regards full-power consumptions, the figure of 0·46 lb. of oil per s.h.p.-hour for all purposes given for the Diesel-electric tanker "Brunswick" is no improvement on that obtained by many straight Diesel tankers.

When cost is not the first consideration, then electrically-operated auxiliaries give a very satisfactory arrangement and enable high economies to be obtained that may well be worth the extra capital cost. This is not in every case light; for a twin-screw cargo vessel of about 6 000 i.h.p. the cost of machinery for a turbo-electric installation was 25 per cent greater than for the straight geared-turbine system. For cargo vessels it would be thought that the exhaust turbo-electric drive would prove very efficient, but here also cost seems to be the determining factor, which makes competition with the other rival systems difficult. The authors state that most small cargo vessels have electrically-operated auxiliaries. In my opinion this statement is inaccurate, and it would be of interest to learn how the authors propose to vindicate it.

Mr. G. Austin: I do not agree with the statement in the Introduction to the effect that for a new vessel the use of electricity for auxiliary purposes is taken as a matter of course. I am afraid that in most cases steam is adopted as a matter of course, and electricity is employed only for lighting, wireless equipment, and small matters of that kind. In passenger ships, however, owners are obliged to use electricity on deck, to do away with the the inconvenience of having steam pipes in passenger spaces and also to avoid the dirt and noise associated with steam winches.

I do not agree with the authors' remarks on page 245 suggesting that contactor gear, especially with the contactors below deck, is the best method of winch control. In the rush after the War, electricity was by no means a favourite for deck machinery; some important vessels used electro-hydraulic plant, while others turned to steam. Indeed, it was at this time that a well-known firm of donkey-boiler makers was kept working at high pressure making boilers to supply steam for winches on motor-ships. In some cases electric winches were actually discarded and replaced by steam winches. In more recent years electrical deck machinery has made progress. It is not, however, because marine engineers are satisfied, that contactor gear has come to be used more freely; but because, in these days of depression, low first-cost is the predominant consideration. As trade revives and the financial situation improves, owners will doubtless turn to the better type of apparatus. It is singular that constant current, which is used in the largest vessel in the world, is classed by the authors as having "similar advantages to contactor control." The qualities of constant current are those also of steam, and when contactor gear can reproduce the excellent characteristics of steam it will then be able to claim some measure of equality with constant current. Deck machinery should be self-contained and watertight. It should not be necessary to have valuable space below deck taken up by contactors or convertors, and the characteristics of the plant should be such that overloads on the motors are converted to reduced demands on the electrical supply system.

On page 250 it is stated that the question of cable-runs should be given more and earlier consideration than has been devoted to it in the past. I think the time has come when something should be done to reduce the enormous mileage of cables and wires on board passenger ships. The system of distribution in common use is responsible for this; it has outgrown its usefulness and has in fact become a danger, since it causes serious congestion and increases fire risk. Why, for example, should so many small circuits be brought to the main switchboard shown on pages 246 and 247?

It would have been of interest if the authors had given some figures of efficiency and capital cost, and endeavoured to justify the turbo-electric drive in the eyes of the shipping and shipbuilding world. In a synchronous system the ratio between turbine and motor speed is fixed, just as much as in a reduction gear, so that when the vessel is run at reduced power by one turbine the frequency is reduced and the turbine cannot be run at its highest and most economical speed. It would seem, therefore, to be somewhat difficult to justify the loss incurred in two transformations of energy, together with possible extra weight and extra cost, in order to eliminate two reverse turbines and reduction gears. That the turbo-electric drive has some advantage in coupling for cruising speeds is, of course, admitted.

In regard to alternating current for auxiliary power, several important shipping companies have considered the question but none has ventured to make the change. No question of transmission of power is involved, since the largest ship afloat barely extends to 350 yards, but it would certainly be desirable to get rid of reduction gear between the turbine and dynamo, because of the hum which can penetrate beyond the engine room. On the other hand, the proportion of motors which could be run at constant speed is small. Forced-draught fans, circulating pumps, and pumps in general, must have a large speed range, and even fans for heating and ventilating systems require to be adjusted to give the necessary water-gauge pressure, or suction, after installation, with further variations in service to suit climatic conditions. It is doubtful whether it would be wise to use alternating current for lighting and hotel services. At any alternating voltage above 33 volts a shock may be dangerous to life, because of the effect in arresting the action of the heart and the fact that a person may be unable to release himself from an accidental contact. A ship with hundreds of cabins, virtually steel boxes, presents worse than "bathroom" conditions everywhere, and danger would lurk in portable metal fittings of every kind. It would be a delusion and a snare to depend on earth connections. If, for any reason, it was considered to be desirable to generate alternating current, it would certainly be found necessary to rectify the major part of the energy produced.

The authors seem to approach the problem of Diesel-electric propulsion with the idea that something is going to break down, and proceed to surround the plant with switchgear which in itself is a source of weakness. Marine engineers have sailed the seven seas since the beginning with but one engine and one propeller, and have invariably come home; and in the case of a multi-screw installation there is never a thought beyond making the plant reliable. Why is it then that, whenever electrical plant is considered, stand-by equipment has to be provided for? Is not a dynamo or an electric motor a more reliable machine than any steam or Diesel engine ever invented? If so, why do we not show our faith in it, and scrap the switchgear?

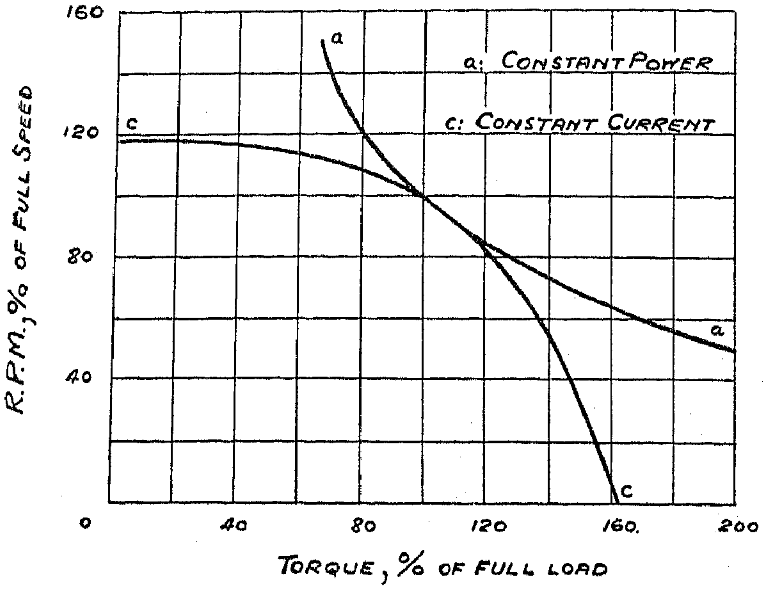

Fig. B.—Diesel-electric propulsion: characteristics of motor.

Referring to the curves in Fig. 10, curve (*b*) has a drooping characteristic produced by opposing windings on the dynamo. It does not represent constant power, but crosses the constant-power line at two points, and approximates to it for about 30 per cent of its range. If it could be flattened at the upper end to prevent propeller racing, the curve would represent good conditions for propulsion. Curve (*c*) is said to be that of a constant-current system, but I think there is a misunderstanding in regard to it. The constant-current motor should be compared with the constant-power curve on the basis of torque and speed, and not on that of volts and amperes (see Fig. B). The corresponding volt/ampere curves would be vertical lines, one long as in Fig. C and the other very short as in Fig. D. Curve (*d*) is one of the curves possible with our self-protecting dynamo, but it is only one of a great variety which can be produced at will after the machine has been made. For propulsion I should arrange it to have a characteristic between curves (*b*) and (*d*), following the constant-power line as much as possible.

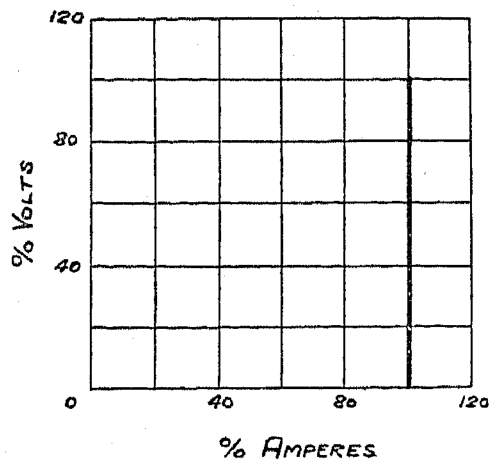

Fig. C.—Diesel-electric propulsion: characteristic of constant-current dynamo at full load.

Turning to page 255, the authors state: "It will be seen that if the generator field is strengthened too quickly before the propeller speed has had time to rise, excessive currents may flow which may cause dangerous sparking at the commutators, and possibly overload the engines," and on page 256 they remark that the generator e.m.f. must not be altered so quickly that the motor back-e.m.f. cannot follow. The self-protecting dynamo referred to above meets these conditions; it adjusts the excitation to a nicety, and prevents these dire happenings. If one uses opposing windings or relays to control the voltage and current, a certain time must elapse before they can come into play, and a further time must follow before their action can become effective. During this time the power demand overshoots the mark and overloads the engine. On the other hand, by using the dynamo referred to, the correction is effected at the air-gaps by the armature cross-m.m.f. itself. The correction is therefore much more rapid.

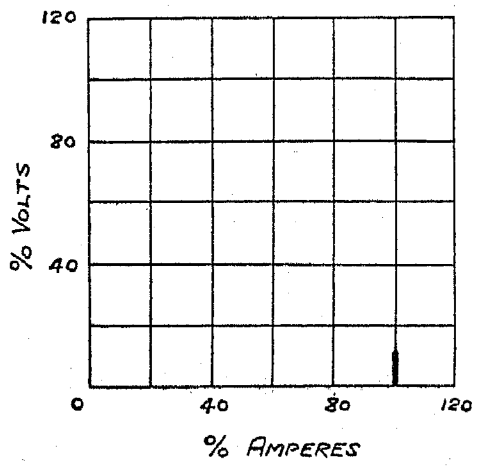

Fig. D.—Diesel-electric propulsion: characteristic of constant-current dynamo with propeller free.

Mr. John Bentley (*communicated*): In the Introduction the authors state what some of us would like to be true, namely, that for new construction, electrical auxiliaries are taken as a matter of course. There are, however, a large number of shipping companies who cannot see their way to equip their ships, particularly cargo vessels, in this way. Many, while accepting electrical auxiliaries for their Diesel-driven vessels, will not do so where steam is available. If it had not been for the Diesel drive, I fear that our progress in this direction would have been even slower than it has been.

The paper also states that electrical operation can satisfactorily fulfil the demands of all drives on board ship (economically, I take it). I suggest that for such drives as windlasses, capstans, boiler feed-pumps, refrigeration, and compressors, steam can still hold its own on a basis of earning power, taking into account interest on outlay, depreciation, output, and adaptability. The steering gear is on the border-line in this connection. I quite agree that there are in many cases advantages which are difficult to estimate in terms of cash value.

When considering cargo ships the extra cost of electrical deck machinery is a serious item which has to be taken into consideration. Taking the present capital cost of an electric winch that will comply with the requirements met with on board ship, it is impossible to show even an equal cost per ton of cargo handled to that of a steam winch. The electric winch will not handle cargo as quickly as a steam winch. This is indicated by the higher speeds which have been specified for the winches on the vessels built in the last year or two. I put this down to the delay of 1–2 sec. caused by the magnetic brake in landing loads, and also to the fact that the armature of an electric motor is limited in its peripheral speed, so that the light-load lowering speed is limited. One of the difficulties a designer meets with when designing the motor for a winch is the wide speed-range required. A deck winch is for most of its life working at loads of 15 to 20 cwt., and the usual speed is about 400 ft. per min., but it has to be capable of a duty of, say, 4 tons at 100 ft. per min. This is equivalent to 26 h.p. (net) in both cases. The natural speed/load curve of a series-wound motor gives 4 tons at 100 ft. per min. and 1 ton at 200 ft. per min.; therefore the series winding has to be diverted automatically to get the speed up to that required for this latter load. The armature on a standard winch has a kinetic energy equal to about 8 times that of the load, and this has a large bearing on the stresses which have to be allowed for when stopping the winch. It is therefore advisable to keep the motor as small as possible, by not limiting the temperature-rise more than is absolutely necessary. It is better to use insulating material which will withstand the higher temperature. By specifying low temperatures the customer may very likely be preventing the designer from giving him a well-balanced machine.

Windlasses and capstans offer similar problems, such as: (1) A high standing torque which has to be limited to a predetermined maximum, so that the machine will stall at a given load. (2) As high a speed as possible, to take in slack. (3) Mechanical stress due to armature momentum. (1) and (2) are met in the constant-current system, and in a less degree by the motor-generator systems, but at a comparatively high cost. (3) is met with to a certain extent by a slipping clutch.

I dealt with some of the problems of deck winches in a paper* published in the *Journal* in 1926. I have recently been occupied in investigating the economic possibilities of the various types of electric winches and have tabulated the relative capital and working costs and degrees of adaptability. I have come to the conclusion that the constant-current system is the most adaptable, but that its high first cost makes it uneconomical. The winch that has the appearance of being the most economical (I have not had an opportunity of seeing one working) is of German make. It has contactor control with master controller, and a load discriminator to adjust the motor-speed/load curve to constant power. Regenerative lowering controls the lowering speed, and a shunt-wound motor is used. The scheme is reasonably simple.

The system of control mentioned on page 245 for refrigeration compressors is in my opinion to be commended. Not only is it efficient but its capital cost is not excessive, and the system can be adjusted so that the starter need only be a double-pole circuit breaker.

With reference to starters and control gear, I agree with the authors that these should be as simple as possible. Most of the complications arise, however, from the desire to prevent misuse by the operator. Many of the mechanical slow-motion devices and interlocking arrangements are worse than the troubles which they are designed to overcome. They invite misuse, as they cause annoyance on the part of the operator. Where the operators are likely to be such that they will not start the machine properly with the guidance of the ammeter, the best alternative is to fit an automatic starter of substantial design. The question of time-delays, particularly on a controller where it is necessary to predetermine the steps (i.e. unit-contactor control) is still a problem. In my opinion there is not a satisfactory timing device on the market. Most of those available are too flimsy, and they all suffer from one or other of the defects which are mentioned by the authors.

I am very interested in the section of the paper dealing with electrical propulsion. The a.c. drive appears to require very selective operation, otherwise the operator will be continually against the interlocks. The d.c. systems seem to be more straightforward, but, as the authors state, for large powers a limitation is fixed by the commutators as regards voltage and current-carrying capacity.

It has been my experience that modifications of the Ward–Leonard system can be made to cover a wide range of conditions automatically, and it is only when we get our basic facts wrong that safety devices for limiting the voltage and load are required. If the system is not exactly right from the beginning, the number of interlocks builds up at an alarming rate. The first Ward–Leonard steering-gear, with which I was concerned in 1910, incorporated a number of correction devices, but to-day this method is automatic on the rotary machines alone, the only switchgear necessary being the motor-generator and the control rheostats. I think that when the designers obtain the correct characteristics of the various parts they are connecting, they will balance the system in such a manner as to do away with many of the interlocks and thus simplify the work considerably.

Regarding the question of applying a.c. supply to the drives on board, referred to by Mr. Saunders in his supplementary remarks at Glasgow, this has been raised from several quarters but as yet not from those concerned with deck machinery. No concrete proposals have been put forward as to how alternating current is to be applied to deck machinery.

[The authors' reply to this discussion will be published later.]

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* *Journal I.E.E.*, 1926, vol. 64, p. 567.

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, LOUGHBOROUGH, BIRMINGHAM, MANCHESTER, AND NEWCASTLE.

Messrs. C. W. Saunders, H. W. Wilson, and **R. G. Jakeman** (*in reply*):—

LONDON.

In reply to Mr. Constable it should be pointed out that the paper covers such a vast field that it might be considered as a basis for as many as 12 other papers of the same length, and, referring to the Table of Contents on page 241, they might be as follows:

(1) Generation, types of vessel, nature of load, types of generator, and systems of supply.
(2) Distribution and use.
(3) Switchboards.
(4) Engine-room auxiliaries.
(5) Refrigeration machinery.
(6) Ventilation.
(7) Deck machinery.
(8) Motor starters and controllers, and motor design.
(9) Hotel load.
(10) Cables.
(11) A.C. propulsion.
(12) D.C. propulsion.

The question of whether a main switchboard should be installed, or several smaller boards spaced round the ship, is always a matter for discussion and different owners have different ideas, but neither presents any difficulties, a fact which rather demonstrates the flexibility of electricity aboard ship.

In passenger liners it is considered by some that quicker service is obtained by having the switchboard at the one point with one or perhaps more electricians on duty so that service can be rendered quickly in case any of the gear shuts down for any reason.

The question of turbo-electric versus geared turbine drive involves a great number of pros and cons, but if full advantage is taken of the maximum steam conditions for both it is reasonable to expect that if two similar vessels were tried out, one with each type of drive, the running costs would be very much the same. Over a long period of running the figures for the turbo-electric drive might be even less. This would particularly be the case where the power required demanded four shafts and where two turbo-alternators could be installed. The 6 or 7 per cent extra transmission loss of the electric drive could be reduced very much by the choice of steam conditions and propeller revolutions until it might be assumed that boilers, condensers, and all engine room auxiliaries, were common to both types of drive. Funnels, shafting, grating, propellers, etc., would be common to begin with.

Any extra cost between the turbines with their high-, intermediate-, and low-pressure casings, and the gears, on the one hand, and the turbo-alternators, control gear, cabling, and motors, on the other, would be only a small percentage of the total installed price of the machinery and a very much smaller percentage of the price of the ship.

The cost of survey of the single-casing turbine with its one rotor, compared with the three ahead casings and rotors, and the astern turbines, together with the opening up of the gears, also favours the turbo-electric drive. The survey of the electrical motors, control gear, and alternators, constitutes a very small job, little opening-up being required. There is a considerable saving in lubricating oil, and this again is on the side of the turbo-electric drive. Further, at very little extra expense, margins in cable, control gear, and air coolers, can be increased to allow extra power to be available when needed for making up time.

Referring to the Admiralty practice of using pipe-ventilated motors, we agree that this is often desirable in practice. In many cases it is necessary to use ventilated motors, and present-day construction is able to cope with the presence of fumes and dirt. Taking for example a traction motor, which has to be ventilated owing to its restricted size, the ventilating air carries metallic dust from the brakes, but the motor can be so constructed that breakdowns are extremely rare.

In reply to Mr. Watson, there is something to be said for using a current in the field windings in order to prevent condensation, but this is liable to complicate the switchgear. We agree that it is advisable to circulate the air.

The question of using one motor to drive the other motor on the same shaft for trimming the commutator is important. It is sometimes very difficult to rig up a separate drive for this purpose.

We are in favour of the use of current-limit control for all hoisting machinery, for the reasons stated by Mr. Watson. Time-delay devices have been used, however, and appear to have been satisfactory. Whilst the use of back-e.m.f. devices is not advocated generally, they have been used quite successfully for small machines which can be started with only one resistance step, and a saving in cost over other types of starter for this class of work is effected by using this type.

The use of very large studs for circuit breakers and switches is undesirable, although the risk of the nuts working loose can be eliminated, provided each of the connecting strips is locked individually by means of lock-nuts. The use of floating nuts between connections is deprecated. For very large switches and circuit breakers laminated connection strips are preferred to studs (see Fig. E).

It is interesting to note that, in order to overcome trouble due to inductive discharge from contactor coils, 500-volt cables have been used, and this bears out our plea for the use of cables of the highest quality. Unfortunately, discharge resistances cannot always be used with contactor coils as this would tend to sluggish operation of the contactors.

It is agreed that the question of personnel to look after this gear should be given more consideration by the authorities than is at present the case, and there should be some certified qualifications allocated to this branch of sea-going engineer. We have advocated very strongly for the last 5 years that the apprentices in electrical work to-day should be accepted by the authorities as having had sufficient engineering apprenticeship to allow them to go to sea and sit for their certificates, and in this way a marine personnel would grow up which would have a thorough knowledge of electricity as well as mechanical engineering. The apprentices in electrical works to-day receive a good mechanical training as well as an electrical training, and constitute a very good type of the rising generation for marine work.

Replying to Dr. Garrard, the fact that the cable aboard ship had not the same life as that on land is unfortunately correct and is shown by the amount of rewiring that has to be done from time to time. The cable used for the work is made by the same manufacturers as the land cable, and their experience has been brought to bear on the subject for many years.

The problem is a difficult one because all the enemies of copper, rubber, cambric, and lead, are present to a very pronounced degree at sea, these being salt-laden atmosphere, salt water, large range of temperature, vibration, oil, mechanical damage, and "working" of ship.

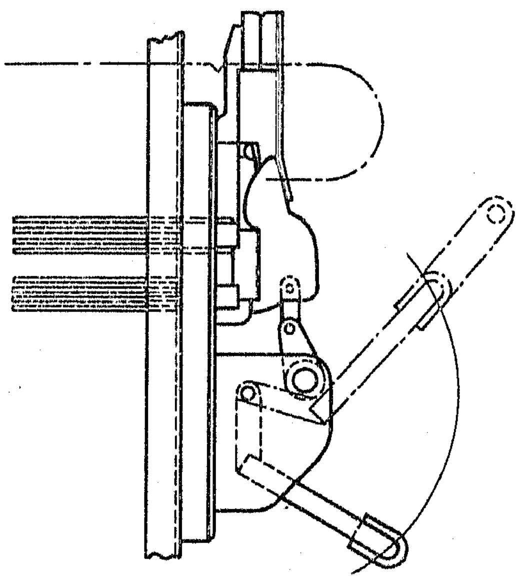

FIG. E.

Simplicity in control of auxiliaries has been attained to a great degree by using efficient and reliable automatic starters, but the problem is a different one when referred to the control of the actual propelling machinery. Auxiliaries are usually installed with a stand-by, and as there are large numbers of them mechanical operation, whilst feasible, is not as efficient, so that automatic starting is a distinct step forward.

Automatic starting and stopping of the propulsion machinery, where there is only one propeller per side of ship, must be considered from an entirely different angle. Throughout the life of the ship the captain's order from the bridge must always be carried out immediately, otherwise the safety of the ship, together with that of perhaps two or three thousand lives, may be involved. The safety of a ship seldom depends on the starting of an auxiliary, although it may do so on rare occasions, but in every case it is dependent on the starting, stopping, or reversal, of the propellers. It is recommended, therefore, that alternative mechanical control gear should always be available for use.

In the follow-up control gear as described on page 255 the speed of the regulator motor is determined by the time taken for building up the fields.

Undoubtedly the attraction to passengers of vessels with electric propulsion has a great bearing on the economics of propulsion machinery, but at the same time the curve shown on the lantern slide, which has been published in another paper,* points towards the fact that since the use of the land turbine makes better use of higher steam conditions, and the choice of propeller revolutions is flexible, the actual question of fuel consumption is brought nearer to the owners' requirements. The Diesel-electric drive for tugs is well worthy of consideration by tug owners as they sell not horse-power but tons pull, and a Diesel-electric tug can exert its full power as pull at, say, 90 propeller revolutions and the tug standing, or at say 110 revolutions and the tug travelling at so many knots. Any prime mover which is directly coupled to the propeller and designed to give its full power at 110 revolutions cannot give this full power at the 90 revolutions of a stationary pull, and as tug work consists largely of stationary pulls there is an undoubted advantage here.

Again, with the Diesel-electric machinery, the load on the Diesel engine can be limited under all circumstances of reversal to the power of the engine, so that no engine margin is required such as would be necessary with an engine that was directly coupled to the propeller.

The principle of bridge control for small vessels, and particularly tug work, has decided advantages in jockeying for position (the gradual tightening on the rope thus saving the breaking of ropes) and for coming alongside piers, but on large ocean-going vessels the advantages would not be so great because whenever they enter port they are accompanied by tugs and do not manœuvre themselves alongside to be tied up as small craft do.

In reply to Dr. Thomson, the points brought out, viz. the absence of astern turbine, cross-over piping, etc., have not in the past been sufficiently taken into consideration when the turbo-electric ship is being considered against the geared turbine ship, but it is to be hoped that all the pros and cons will be gone into in the near future.

Exhaust-heat boilers in Diesel-driven ships would probably not be employed for driving an auxiliary generator only, but as a rule the steam from these boilers is utilized in other directions, which then makes their use economical.

The remarks on the comparison between steam steering gear and electrical steering gear might also be used for practically all the deck machinery and the engine-room auxiliaries, and in fact all the auxiliaries in the ship. It would be practically impossible to apply a steam engine with its steam and exhaust piping to all the motors as given in Table 2 on page 243, and therefore a great number of these auxiliaries, all of which are essential in a modern passenger liner, would have to be omitted, so that, apart from the economy in use of electricity for these auxiliaries, the passenger ship with the electrical auxiliaries is more likely to attract passengers than the one with the steam-driven auxiliaries.

The figure of 0·45 lb. of fuel per s.h.p. has not been obtained in a turbo-electrically driven ship, nor in any other steam-driven ship, and is more like the figure for a Diesel-driven ship. The consumptions for propelling s.h.p. only, as distinct from consumption per s.h.p. for all purposes, are really invaluable figures for comparison, and until they can be compared on several classes of vessel it will be difficult to make the comparison, since this figure of pounds of fuel is always dependent upon boiler efficiency, etc. It would, therefore, be better to have pounds of steam per s.h.p., when the figure is then measured between the turbine stop-valve and the propeller shaft. For turbo-alternators these figures of pounds of steam per kWh, which are easily convertible to s.h.p.-hours, can be obtained in the power stations ashore. The efficiency of the motor can be readily ascertained. Readings of s.h.p. have been obtained in actual practice with a degree of accuracy that is remarkable. In one case four indicating s.h.p. meters read every half-hour for 16 hours, and compared with four integrating s.h.p. meters in the same circuits, only varied 20 h.p. on a total load of 18 000 s.h.p.

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* C. WALLACE SAUNDERS: "Turbo-Electric Propulsion," *Transactions of The Institute of Marine Engineers*, 1934, vol. 46, p. 88.

With regard to Fig. 9, a vessel of 21 000 tons displacement with 20 000 s.h.p. developed, and doing 21 knots, was stopped and just moving astern in 2 minutes 50 seconds. This operation can be an everyday occurrence as it is not detrimental to the engines, the turbo-alternator never reversing and the motor being designed to do this as often as required. As an instance of this, on the motors in rolling-mills full reversal takes place every minute or so.

Kinetic energy cannot be given up by the propeller out of the water unless its speed decreases. Actually, in the time available, the speed tends to rise, since the reduction in engine torque is not instantaneous. With any twin-screw ship, in a rough sea, there is always a tendency to "yaw" since the propulsive effects of the two screws vary periodically. The helm is used to keep the mean course correct.

Replying to Dr. Whitehead, propulsion cable-runs receive better consideration to-day from the naval architects, and 3-core cable is used considerably, thus obviating any heating effect on the seal.

The use of cambric-insulated cable on ships has increased over the last few years, and to-day it is used for a large number of purposes. The smaller cables, however, are rubber-insulated and hot spots are, as a rule, avoided.

In reply to Mr. Hardy, undoubtedly electricity made slow progress in convincing the shipowner and the shipbuilder of its economies aboard ship, but on the auxiliary side this has been established. On the propulsion side a great deal of pioneer work has been done and much more interest is being taken in it, and no doubt electric propulsion will become more common as time goes on.

In reply to Mr. Beara, the comparisons obtainable with electric drive by accurate measurement of the s.h.p. must undoubtedly be of great service to naval architects and shipbuilders for checking up their data, and if a class of vessel were to be built and one of the ships laid down as electric, the full-size model data should provide most useful information to the shipowner. The difference in power between shafts indicating a damaged propeller is interesting as showing where electrical instruments can give information, and by interchanging instruments between port and starboard, thus eliminating possible instrument errors, this information would be obtained definitely, even without dry docking.

The use of essential and non-essential tripping is undoubtedly of benefit in keeping vital services running and has proved very effective in service.

The question of lead covering of cables being subjected to vibration and cracking has practically ceased to exist owing to the lead alloys now employed.

In reply to Mr. Chase, the use of batteries aboard ship has of recent years been much extended to give emergency steering facilities, skeleton lighting through the ship, including navigation lights, all signalling apparatus, switches, call-bell system, telephones, and fire alarms, should the main busbars become dead. This application of the battery is very important because a ship with her passengers need never be in darkness which would tend to cause a panic in a heavy sea way, and further, steering facilities are available in close waters and sufficient illumination is available in the engine room to clear the faulty machinery and get the busbars alive again. Batteries offer a final stand-by which is reliable and undoubtedly is a step in the right direction.

In reply to Mr. McClelland, the use of Diesel-driven generators in a steam-driven ship has one great advantage from a technical point of view, and that is that authentic figures would then be obtained of the pounds of fuel per s.h.p. for propelling only, the rest of the ship's consumption being separated entirely from the boilers. This may not be sufficient reason to install them, but there are ships afloat with this arrangement which no doubt shows economies.

The fact that Diesel-driven generators are installed does not, as a rule, involve an increase in the size of the engine-room, but their upkeep would no doubt be heavier than that of the steam-driven sets.

The steering-gear motors, each of which is capable of doing the full duty, should always have separate circuits run from the main switchboard in the engine room direct to their starters, and one practice is to have double-throw switches with two sets of fuses so that, in the event of one fuse blowing, the circuit is immediately available by throwing the switch over. Should there be a fault which blows this fuse, then of course the other motor with the similar circuit must be depended on until the fault is cleared. These circuits on the main switchboard are placed port and starboard, so they are separated along the busbars. The fuses are liberally rated for this steering duty.

Mr. McClelland prefers Ward–Leonard control for heavy machinery, and it is agreed that this system gives entirely satisfactory results. Considerable improvement has been effected in the booster system during the last few years and there is no doubt that at the present time its performance is little, if any, inferior to that of the Ward–Leonard control or even of steam. The fact that reversal of the motor has to be carried out by reversing the armature on the booster system is certainly one point in favour of Ward–Leonard control.

In reply to Mr. Grove, it must be pointed out that for turbo-electric propulsion the turbines run at variable speed and always in the same direction, while Diesel engines for electric drive run at constant speed and are unidirectional. Each individual ship on its individual trade has to be treated on its merits, and there are cases where the electric drive will show actual advantages. Where this is so there need be no fear of its performance or its life.

On existing turbo-electric passenger vessels, from the passengers' point of view, quiet running, absence of vibration, etc., are advantages, and these vessels are all pronounced a success.

Replying to Mr. Reid, the fact that, by fitting electric drive, a naval architect can show greater earning capacity of ship, is an argument that is very helpful to the adoption of this form of drive, and is an addition to the technical arguments that are usually put forward for its adoption.

In the case of the Diesel-electric tug there is a definite advantage in the lower h.p. necessary for a given tow-rope pull. It is interesting to note that, compared with coal-fired steam cargo ships, the dead-weight cargo capacity may be increased from 10 to 12 per cent and the measurement capacity to as much as 15 per cent. Its use in trawlers making 3-week voyages is also very interesting and, of course, in vessels where the port load is of big proportions undoubtedly has advantages and it gives a license in engine and propeller revolutions from which economies might easily accrue.

LOUGHBOROUGH.

In reply to Mr. Nichols, the data obtained from the full-size ship when on trials, for comparison with the data obtained on the models of 1/50th or 1/100th full size, would be arranged to be taken at suitable draught and trim of ship.

Replying to Mr. Heath, the increased use of electricity is not considered to have any bearing whatever on fires that have recently occurred on various ships and it is thought that it would be very difficult to prove that any of the fires were due to any part of the electrical installation. If it were so, there would be numerous instances of fires that were got under control where evidence showing that they were due to faults in the electrical equipment had not been destroyed.

In reply to Mr. Nixon, the information regarding the "Queen Mary" and the "Normandie" is quite interesting and the performance of the two vessels will be watched with great interest.

The application of electric drive to trawlers is dependent on the size of trawler, her range and length of voyage, etc. There should be a case for trawlers that are out for two or three weeks at a time, and there is no reason why the installation should not be run by the existing personnel just as Diesel-electric tugs are where there is no special personnel employed.

Replying to Mr. Driver, the voltage in the case of d.c. Diesel-electric propulsion for large ships is made as high as possible in order to reduce the size of the commutators as well as the cables. Since the centre-point is earthed and all live parts are protected, there is no danger of shock.

The remark about choosing any value of frequency applied to propulsion only. We agree that if alternating current is used for the auxiliaries it would be advisable to use a standard frequency, although this advantage is limited since there is no standard throughout the world.

With regard to temperature-rise, we would refer Mr. Driver to Lloyd's new rules which have been compiled in collaboration with all the interested parties.

In reply to Mr. Wilson, the curves shown on the lantern slide were published in a paper on turbo-electric propulsion read before the Institute of Marine Engineers in February, 1934.* In this connection, and if the curves are correct, then the whole of the installed machinery of both the geared turbine and the turbo-electric proposition for a given power is common, except the turbine and gears on the one hand, and the turbo-alternator, control gear, cable and motors, on the other hand. As this portion of the installation in the first case constitutes a small percentage of the total installed machinery, the only difference in price or weight would be over this portion of the machinery, and is therefore a very small percentage of the whole. The many other advantages should at least justify this small extra cost. The use of automatic starting of auxiliaries, provided a reliable time-delay is available, such as a clock gear, is undoubtedly a step forward in giving long life to the electrical machinery, because any apparatus that can only function always as is predetermined must of necessity derive benefit from this.

Mr. Wilson's comments regarding fires aboard ship are interesting, and no doubt will receive the attention of the inspecting authorities. Provided the cable and other electrical equipment generally are properly installed there is very little risk of fire due to their failure.

BIRMINGHAM.

In reply to Dr. Kahn, the upkeep of electrical machinery aboard ship to-day is undoubtedly very small; as an instance of this the total cost for 12 months' guarantee period of the whole of the electrical equipment of one of the vessels mentioned in the paper, of which the particulars are given, amounted to £32. This included the propelling machinery, all auxiliary machinery, and the hotel equipment.

Dr. Kahn has brought out clearly the different conditions with regard to generation and distribution which obtain on board ship and in land stations. He shows that too close a comparison is not justifiable. We agree that mechanical considerations as well as power factor have established the synchronous motor as the most suitable for propulsion. It is true that the stability of the generator and motor as a unit must be considered, and it is interesting to note that they work with constant excitation instead of constant voltage, which is the case in land practice. The conditions, however, are not quite so difficult as he suggests, since during a reversal the motors are no longer synchronous but act as induction motors.

Dr. Kahn gives a general survey of the present position in regard to the choice of alternating or direct current for auxiliary supply. The replies to his and other speakers' remarks in this connection will be summarized later in the discussion.

In reply to Mr. Turnbull, the housing of the electrical gear in deck houses or below deck is an economic problem for the shipowner and in many cases has been proved to be well worth while without sacrifice of cargo or passenger space, because ventilated machines can be installed showing a big saving in initial outlay, and upkeep is very low due to accessibility and housing from weather. It is quite possible to put electrical machinery on a deck just as steam winches are placed, but the sea atmosphere and salt water, etc., are just as devastating to steam winches as to electrical machinery and constant upkeep is required on "field days" at sea and overhaul in port.

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* *Loc. cit.*

The totally enclosed motor has to have a watertight joint protection broken even to adjust the brushes, and to put the control gear in the bedplate, whilst quite feasible, is not as good a job for the owner as the other method. It is entirely a question of the economics of the job, otherwise one or other would prevail.

The fact that it was necessary to caulk all the joints of the motor with red lead before beginning a voyage points to the motor and control gear being intended to function for several voyages without even being looked at.

The question of upkeep and repair of marine electrical plant raised by Mr. Richardson has been replied to elsewhere; whilst this figure must be regarded as exceptional there are Diesel ships with complete electrically-driven auxiliaries, including cargo winches, etc., where the upkeep is very small indeed. It is difficult to give the dimensions of engine rooms, as they vary so much, according to the owners' requirements, the trade in which the ship is engaged, and the type of machinery used.

The results of tests on trials vary, of course, with each type of vessel and comparison would be difficult, but turbo-electric propulsion or Diesel-electric propulsion, with full power available astern, undoubtedly should stop a vessel more quickly than any machinery that has less than its full power astern, and, whilst the hull of the vessel enters into this question, at the same time the rate of working up to the full power astern in keeping with the vibration of the hull is quicker than in any other form of propulsion.

The question of electrical heating of cabins and public rooms, etc., mentioned by Mr. Engholm, has been in existence for a considerable number of years, the type of heater being one that must not be liable to cause a fire. These take the form of water radiators with an immersion heater, and the like. The air brought down through the ventilating system from the top deck to the cabin is also heated, but usually by means of steam heaters in the fan unit. No ship has yet been electrically heated throughout and figures of cost are probably not available.

In reply to Mr. Minshull, the failure of the lead on lead-covered cables due to vibration has been overcome by the use of binary and ternary alloys.

The use of H.R. cable for certain spaces and duties has been in practice for some years and seems to be giving satisfaction.

The use of alternative mechanical control, referred to by Mr. Coates, has been replied to elsewhere and reasons are given for its use.

In reply to Mr. Rawll, the question of standardization of voltage has been dealt with in Lloyd's new Rules (extract No. 16, dated 21st June, 1934).

Mr. Peake has brought out a point which should be considered fully by owners, because it is undoubtedly of the greatest possible advantage to carry out a full-load or even overload test with the components assembled at the makers' works. In the case of small d.c. equipments the complete machinery, including control gear, can be tested as a combined unit in the shops. These tests can be made much more severe in the shops than in the ship, particularly in regard to manœuvring.

Mr. Royle refers to the increasing use of automatic starting gear. There is no doubt that this type of starter is well suited to use on board ship as it relieves the operator of all anxiety as to the rate of starting and also gives the facility for remote control which is desirable for many of the auxiliaries. The success of this equipment, however, depends entirely on the use of a reliable time-delay, and the clockwork timing device fulfils this condition. Air dashpots must of necessity suffer from similar disadvantages to oil dashpots owing to the fine clearances which have to be allowed if the device is to be effective. Mercury switches do not appear to be suited to shipboard use as consistent operation may be affected by the roll of the ship.

MANCHESTER.

Mr. Juhlin points out that atmospheres laden with fumes and oil vapour are often met with in land practice, so that the insulation used with success for many years in Diesel-driven stations is equally satisfactory from this point of view on board ship. His remarks on various types of drive are interesting.

Although we recognize the importance of the additional power supplied by an exhaust steam turbine, we were not able to do more than mention it on account of lack of space.

The question of condensation, referred to by Mr. Hoseason and Mr. Trickett, is one which has never worried us very much. The company with which we are associated has a very large number of totally enclosed motors installed in exposed positions on board ships which ply in various parts of the world. Many of these motors have been in service for years and we have never heard of a solitary breakdown either of field coils or armatures during the past 6 years at least.

We agree that breathing may permit considerable condensation to collect in a machine. The best way of dealing with this is to have a small hole in the lowest part of the shell so that any moisture which drains down can run away. We have never considered using anti-condensing paint, the insides of the shells merely being sprayed with black insulating varnish or painted with a white paint.

Field coils wound with cotton-covered wire are generally vacuum-impregnated in bitumen, and ample creepage distances to earth are provided for. The main slot insulation in armatures consists of micanite suitably disposed; the coils are impregnated in varnish and dried before insertion in the slots. Completed armatures are given two varnish treatments and finished off with one or more sprayed coats of a bituminous finishing-varnish.

Referring to Mr. Trickett's experience with field coils which broke down, it is not clear how they were insulated. If the wire were wound direct on the solid micanite spools and then impregnated in bitumen it is probable that the bitumen did not penetrate to the full depth of the coil. This often happens if very thick bitumen is employed for impregnating purposes and the coils are more than about $1\frac{1}{2}$ in. deep. We should not expect this trouble to occur if the coils were wound on formers and impregnated, and the micanite spools, consisting of a centre and loose cheeks, were fixed afterwards. The use of untreated leatheroid as suggested might be useful in dealing with the absorption of a small quantity of moisture, but we consider it would be very dangerous if used in coils which stood unused for long periods in extremely damp situations.

With regard to the series system of operating winches, we state that full-load current has to be carried while it is working. We agree with Mr. Trickett that motors are cut out in the "off" position, but the controller contacts still have to carry the full current.

In reply to Mr. Sills, provided fuses are installed with due regard to the capacity of the circuits with which they have to deal, and provided they are used in engine rooms or other spaces set aside for control gear, there is no danger of fire. The question of using high-rupturing-capacity fuses is really a matter for the inspecting authorities to deal with. We agree that such fuses are very suitable for use on ship, but again the question of enclosure is important. The replacement cost of this type of fuse is rather heavy, and provided owners are prepared to face this there is no reason why they should not be used.

In reply to Mr. Evans, the types of individual starter in general use are automatic, drum, counter-e.m.f., and direct switching. The last two are only suitable for small machines, and the others may be used for all types of motor. If remote control is required the automatic type must be used, and we prefer it for all duties for the reasons given in the paper. The drum type described by Mr. Evans is the best alternative and in some cases may be cheaper.

The preference tripping system is usually connected to the shunt coils of the circuit breakers controlling the various outgoing circuits, although it may be, and sometimes is, connected to the overload trips of the individual motors where the motors are on the common starter.

The question of bridge control is one which excites much discussion between the engineers of a ship and the deck officers, and is a matter for individual owners to decide in accordance with their particular requirements. Bridge control for a.c. propulsion is quite feasible and, if owners want it, manufacturers can readily meet their wishes.

Replying to Mr. Johnson, there is no doubt that the steam winch is a really reliable job, but it is wasteful and owners are gradually appreciating the fact that the electric winch, whilst giving equal service, is much more efficient.

There appears to be a considerable difference of opinion regarding the use of ball and roller bearings, and in this connection it should be noted that not only are these standardized by almost all makers of electrical machinery, motor-car manufacturers, and machine-tool makers, but they are now being largely used for traction motors where the service conditions are of the most severe nature. They must be chosen with due regard to the situation in which they have to work, and where the maximum degree of silence is required sleeve bearings should always be used.

Mr. Johnson and other speakers refer to machines situated in places where heavy vibration occurs. Horizontal-spindle machines, such as steering-gear motors, provide an exception to the general rule and for machines such as these which may have to stand for prolonged periods under heavy vibration the question of fitting journal bearings must be considered.

Sleeve bearings often require attention from watch to watch in order to ensure that the oil level is maintained, whereas ball and roller bearings only require fresh grease every 6 months or so.

Mr. Johnson and Mr. Trickett consider we have been too cautious in our claim for the suppression of magnetic hum in super-silent machines. We agree that in a large number of cases the "minimum" is so low that the hum is imperceptible.

The question of cost referred to by Mr. Turner, must be studied in all its aspects and with particular relation not only to first cost but to maintenance costs, savings in space, better arrangement of ship, and so on. Each individual job must be considered on its merits and it is impossible to give definite figures except in regard to a definite proposal.

The status of the electrical engineer on board ship has been dealt with elsewhere in this reply.

NEWCASTLE.

In reply to Mr. Mallinson and Mr. Pomeroy, it is quite true that details, not only of design but of care in installation, choice of system, and the use of the right type of cable, and so on, constitute the difference between success and failure. It is only by the co-operation of owner, builder, naval architect, and manufacturer, that success has been and will be achieved. Planning at the right time, and especially of cable runs, is of the utmost importance and the question of inspection is equally so.

In reply to Mr. Oliver, the question of the distribution of power when circling is a matter for investigation by naval architects. The figures in the paper are a record of actual readings and have never been produced before, similar conditions never having arisen. To assist in the interpretation of the readings, it must be remembered that the steam inlet to each turbine was limited to full steam. In case (*a*) the port turbine supplied $32 + 16\cdot5 = 48\cdot5$ per cent and the starboard turbine $28\cdot5 + 23 = 51\cdot5$ per cent of the total power. In case (*b*) the port turbine supplied $17 + 34 = 51$ per cent and the starboard turbine $27 + 22 = 49$ per cent. These figures are practically half of the total in each case. The ship was running at the same speed in both cases and the steering was by helm only. There was no difference in power factor or excitation between the two cases.

Mr. Oliver and Mr. Beaty ask about the reduction in speed when switching. At low frequencies the reactance of the circuit becomes small compared with the resistance of the starting winding, so that the current taken for a given torque is decreased. The actual value of 1/5 speed is for convenience in design.

Replying to Mr. Beaty, the maximum torque as an induction motor is between 80 and 100 per cent. There might possibly be a limited field for induction motors for propulsion, but there are certain drawbacks with regard to mechanical construction and power factor.

Mr. Cross refers to the automatic starting of the emergency generator when the main generator breakers trip. Whilst this is quite feasible it would entail the use of a very large-capacity battery and it would appear to be preferable to utilize the battery for running the emergency lighting and steering-gear motors direct. This can be brought into operation automatically when the main busbars become dead, and many large modern ships are so equipped.

Mr. Clouston correctly points out that much of the thought which has been given to electric propulsion by marine engineers has been due to their experience of the reliability of electrically operated auxiliary machinery.

In connection with the booster control of deck auxiliaries it should be explained that the windlass or capstan motor is usually wound for rather less than double the line voltage, and it is regretted that this point was not made clear in the paper. It is desirable to limit the voltage on positive boost so that the booster works well below saturation point over this portion of the range in order to obtain the maximum voltage response for given changes in current. The generator also develops less than the line voltage in the negative direction, and the first control step is obtained with a small voltage applied to the main motor, this resulting in a very convenient handling first step.

Although, theoretically, stalling may be effected in the manner described by Mr. Clouston, i.e. by the reversed series winding taking charge, it is sometimes found that a booster designed for this purpose is uneconomically large. It is usual to employ a current-operated stalling relay which lifts on overloads and reconnects the shunt field as on the first or second controller step, irrespective of the actual controller position.

Common Starter.

Many speakers at various Centres have commented upon the common starter. The replies to these may be summarized as follows.

Several speakers consider that the use of common starters introduces complications of wiring and switchgear. The only extra wiring involved by the use of these systems is one 7-core cable consisting of 5 small wires for control and interlocks, together with one shunt lead between the motor unit and the switchboard, and one spare core. The control unit itself can be mounted at any convenient position and usually takes the place of the motor terminal box. The cable run is therefore a straightforward one between the main switchboard and the motor, and does not have to be diverted by means of unsightly and sometimes dangerous loops into starters situated at inaccessible positions, often remote from the motor.

The working portion of the equipment is situated either at the main switchboard or at some central position where it is readily accessible for overhaul and where the illumination is usually good.

The starter itself, in one system, consists of a very simple and robust motor-driven drum controller, and has the advantage that by means of a change-over switch a duplicate starter can be instantly brought into use for any machine.

The drum makes one revolution per start and is then in position for starting another machine.

The contactor panels for each machine are simpler than individual starters, there being three contactors only as against four or five or more because no accelerating contactors are required. The contactors can readily be made dead by means of isolating plugs, and the whole of the equipment is easily accessible for overhaul. It is interesting to note that after 5 years' experience with this equipment afloat we have found that the operators in charge invariably preferred the common starter to individual starters, and several owners have repeated it in new ships.

Mr. Watson and others mention that after a shut-down the time taken to start up is longer with the common starter, but it is a fact that the whole of the essential engine-room auxiliaries can be started up inside 2 minutes.

Dr. Garrard refers to the use of contactors for the common starter. In one of the systems described these are used throughout, and in the other only the line and starting connections are completed by means of contactors. In the latter scheme the motor-driven drum starter was chosen because it was considered to be the most suitable means for starting numbers of motors of widely varying powers.

Mr. McClelland is correct in assuming that the maximum advantage is derived from the use of the common starter when the motors are situated in close proximity to each other. It is usually adopted for engine-room motors and is sometimes used for the refrigeration machines where these are situated in close proximity to the main engine room. It has been found in practice that there is a considerable saving in space and in weight due to the small number of contactors which can be used, and moreover only two starting resistances and drums are required, including a duplicate starter for all of the machines. Where individual starters are used these are often much larger than the machines they control, and the cases, in addition to taking up considerable space, add greatly to the weight of the equipment. It is agreed that the applications of this system to land work are limited, but it has been used to advantage in a mill where a number of large motors are situated in close proximity to one another. In one instance an installation is working in a paper mill controlling twelve 300-h.p. machines.

POWER STATIONS AND THEIR EQUIPMENT.*

By I. V. Robinson, Wh. Sc.

Since the last review on this subject was published† the economic depression has been the dominating feature here and in all industrialized countries, and therefore there have been no striking developments in the equipment of power stations. During the past 18 months the author has been privileged to visit many power stations during a tour round the world, and everywhere there was the same report. The load had so fallen, instead of increasing, that extensions had not been made, nor were they being seriously considered. This was very noticeable in the United States, and was still the state of affairs during a short visit in September, 1934. A static condition cannot, however, be maintained. Where there has been too little to construct, those engineers who would under normal conditions have been fully and profitably occupied in construction have turned their attention to the perfecting of details in design and to the consideration of the direction in which future changes will develop.

TURBINES.

Size of Turbine Units.

There has been no general demand for units of great capacity. In the United Kingdom a set of 105 000-kW capacity is under construction for Battersea and will be available for use early in 1935. The 75 000-kW sets (Barking) mentioned in the previous reviews are working, but no other sets of that size have, as yet, been constructed. For the selected stations the sizes of plant ordered have usually been 30 000 kW or 50 000 kW, but in some of the smaller stations units of 15 000 to 20 000 kW have been installed. The 50 000-kW sets run at 1 500 r.p.m., and the other sizes at 3 000 r.p.m. In the United States there has been no increase in size beyond the previous maximum of 208 000 kW at Chicago, a 3-axis machine. On the Continent the position is about the same as in the United States.

Some manufacturers report that they would be prepared to construct turbines up to a capacity of 250 000 kW at 1 500 or 1 800 r.p.m., if there were any need for them and also provided that they could be transported. Both provisos appear to be effective bars to the actual construction of such mammoth units.

Steeple Compounded Turbines

It was suggested three years ago that the steeple compounded turbine was only a passing fancy. Those engineers who have responded to a question regarding it suggest that its sole advantage is the reduced floor space occupied. Floor space can rarely be so valuable, however, as to compensate for the greater difficulties in adjustment and repairs. In an installation in New Jersey (South Amboy) visited by the author, ground for extension appeared to be available by the tens of acres. These steeple compounded sets are running well using steam at a pressure of about 1 200 lb. per sq. in., this being perhaps the only station designed for such a high pressure and having no medium-pressure plant. A 110 000-kW steeple set in the Ford motor works has been so satisfactory that it is now being duplicated. The fact that it has not been adopted in cities such as New York where land is valuable, however, leads to the thought that steeple compounded turbines are without hope of posterity.

Medium-Size and Small Turbines.

There has been increasing activity in regard to small turbines, particularly for industries requiring process steam. These are usually rated at less than 5 000 kW, but there are larger units. Some of them appear to be all valve chests and valve gear, with a cylinder tucked away behind, apparently an unimportant item in the unit! They might be called "steam busbars," with the incoming and outgoing steam corresponding to the generator and feeder panels.

There has been considerable development in the so-called combined turbo-generator sets, i.e. sets in which the turbine is mounted directly upon the condenser and in which part of the turbine cylinder and the condenser shell are frequently the same casting. Such sets have proved to be very convenient up to about 3 000 to 5 000 kW, as they can be erected with the minimum of delay and involve practically no foundations but only the provision of a suitable floor.

House service sets in large stations have perhaps shown some change. There appears to be a preference now for mounting the auxiliary alternator on the main turbine shaft, so that the auxiliary power may be generated with the maximum efficiency. In order to provide starting current should the station be isolated and standing, a unit of about 2 500 kW is installed, designed to allow of extremely rapid starting, with no attempt at efficiency, and arranged for remote control by means of battery current. These units appear to be gaining in popularity.

Another use for medium-size turbines is as a reducing valve in stations with two steam pressures, say an old steam system of 300 lb per sq. in. or under, and a later one of 650 lb. per sq. in.

Turbine Operating Conditions.

In the last review it was suggested that the generally accepted maximum inlet conditions were a pressure of 600 lb. per sq. in. and a temperature of 750°–800° F. Now in the United Kingdom the popular maximum pressure is still 600 or perhaps 650 lb. per sq. in., but with a temperature of 800–850° F. These figures also represent the general practice in Germany. These conditions are in regular use for sets of 30 000 kW and upwards, but for 20 000 kW the pressure is generally lower, say not in excess of 400 lb. per sq. in. There is no hard and fast line, however, as 600 lb. per sq. in. is being used on a 15 000-kW set. Similarly for the smaller sets the upper temperature may be only 750° F.

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* A review of progress.

† *Journal I.E.E.*, 1932, vol. 70, p. 135.

Mention was made in 1932 of a British-built turbine in an American station (Detroit) designed for a temperature of 1 000° F. Considerable experience has now been gained with this turbine, which is running satisfactorily. Great care is needed, however, in controlling the operation of the superheaters, which, to quote the words of the chief executive officer of the operating company, has to be done with "precision comparable to an exact chemical process."

The Detroit experience lends point to one turbine builder's suggestion that beyond 850° F. the advances should be 25 deg. F. at a time. The Detroit machine of 10 000 kW is too small for modern stations, and it remains to be seen whether fresh and perhaps greater difficulties are encountered with units of 50 000 kW and upwards as needed in most large stations. The Detroit Edison Co. have decided that their new and larger turbines at Delray and Connors Creek shall be designed to operate with steam at a temperature of 825° F. This 1 000° F. turbine has focused attention upon high temperatures; one manufacturer has stated that he is willing to offer reasonable-size units working at 1 100° F., and that he is looking beyond that temperature. It is suggested that 1 000° F. can be used with 3 000- or 3 600-r.p.m. turbines more readily than for lower-speed machines, owing to the smaller dimensions. Will this lead to small geared high-pressure cylinders at high speed, with the other cylinders running at a lower synchronous speed? This is probably a much better proposal than the vertical-compounded or steeple-type turbine to which reference is made elsewhere.

Another British-built machine of 24 000 kW for Russia is designed for 1 763 lb. per sq. in. and a temperature of 932° F, whilst the 36 000-kW 1 700-lb. per sq. in. set in Czechoslovakia, mentioned in the last review, has now been at work for a long time and is doing well. During the year ending 27th February, 1934, it was in service 7 987 hours (91·2 per cent), and generated nearly 70 000 000 units.

This increasing use of high pressures and high temperatures has called attention to the available knowledge of the properties of steam. Until recently, tables containing data for high-pressure steam were little more than a sanguine extrapolation of data observed at lower pressures. Meetings have recently been held (London 1929, Berlin 1930, and New York 1934) of the International Steam Table Conference, consisting of actual investigators into the properties of steam, and it is evident that this body will eventually tabulate well-authenticated data regarding the properties of steam up to pressures of 4 000 lb. per sq. in. This co-operative work was initiated in 1922 by the British Electrical and Allied Industries Research Association. The Conference had not intended to go beyond a temperature of 550° C. (932° F.), but once more practice in the station has outpaced research in the laboratory, and the upper limit of temperature will have to be raised.

As to reheating, views are still about the same as they were three years ago. With 650 lb. per sq. in., 850° F., reheating is not needed, and as the plant efficiency is not greatly improved by employing higher pressures and temperatures with reheating, many engineers prefer to remain, for the time being at any rate, on the lower operating level.

The trouble met in reheating turbines of dealing with the large volume of steam in the system after the governor valve, when the set has to be shut down, appears to be solved by one firm by the use of a differential control gear. In this, in the event of the load falling more than a predetermined amount in advance of the drop of pressure in the reheater, the latter is automatically isolated from the low-pressure end of the turbine and the steam in the reheater is bypassed direct to the condenser.

In endeavours to avoid reheating, great efforts are being made to eliminate moisture in the steam at the tapping points, and special scoops have in some cases been fitted at other points in the expansion to catch and remove moisture. Whereas three years ago it was difficult to get any expression of opinion as to the effectiveness of these devices, one maker now quotes actual figures, but does not claim that more than 25 per cent of the moisture in the steam is removed. Even this result, comparatively small, is well worth while.

For the three 50 000-kW sets at Dunston, reheating is adopted. The initial conditions are 600 lb. per sq. in., 800° F., and reheating is at 120 lb. per sq. in. to 800° F. These conditions are not such as necessarily involve reheating, and in this respect the installation is probably something of a pioneer. These conditions represent a considerable advance over those of an earlier reheating installation at Barking, where the initial conditions are only 350 lb. per sq. in., 700° F., and reheating is to 700° F. This unit is working well.

Reheating involves greater capital costs, and during recent years capital costs have been scrutinized very carefully. In England, in spite of the competition for maximum thermal efficiency engendered by the thermal returns of the Electricity Commissioners, a very healthy regard for the effect of higher capital costs upon total costs of generation has always been evident. Still, without the pioneer, advances towards more efficient operating conditions would not be made.

TURBINE BLADING.

There does not appear to have been any great change in blading material. In the neighbourhood of the dew point the most exacting conditions are met, and here stainless steel containing 12–14 per cent of chromium is used by many builders. For the last few rows of blades, which are subject to a water bombardment, this is not satisfactory, and one means of overcoming this trouble has been to protect the blade edges by harder material. One builder tried 17 different materials on one wheel, and found that stellite was the best resistant to erosion. This material is used by many firms. In one instance this protecting edge covered only one-third of the blade length, but it was found advisable to lengthen it to two-thirds of the blade.

FEED-HEATING.

No great change is to be reported in regard to feed heating. During the past three years there have been no new major installations of feed-heating turbines in Great Britain; the largest installation is still that at Billingham. Here the total feed to the high-pressure boilers is 11 900 tonnes per day, the whole of which (less boiler blow-down loss) is passed to primary turbines operating at 630 lb. per sq. in. (gauge), 833° F., and exhausting at 275 lb. per sq. in. (gauge). Of the total quantity exhausted at this pressure, 6 930 tonnes per day are used for process work, 1 130 tonnes pass to condensing turbines, 800 tonnes to independent high-pressure feed-heaters, 60 tonnes to air ejectors, and the balance of 2 620 tonnes to special feed-heating turbines providing a final feed temperature of 401° F. after the independent high-pressure heater.

For the central-station unit of 20 000 kW and upwards the final discharge temperature is sometimes as high as 360° F., but the number of feed-heating stages generally does not exceed four. In the new station at Trebovice (Czechoslovakia), however, the final temperature is 424° F., and this is reached in only three stages plus a de-aerator heater in which there is a 50 deg. F. rise. A temperature-rise of 60 deg. F. per stage is not often exceeded. The heaters on the discharge side of the feed or intermediate booster pump are generally provided with an automatic by-pass to cut out the heaters should a tube fail.

Evaporators to supply the make-up feed water are incorporated in most of the large plants, taking steam from one tapping and discharging vapour to the next lower pressure heater, and thus working over a temperature range of 50 to 60 deg. F. To provide for low-load conditions the steam supply for the evaporator is not taken from the higher-pressure tapping points, so that, when the load and pressures are low, most of the heating may be done in the stages between which the evaporator is situated. Further, there appears to be less priming when the evaporation is at about atmospheric pressure.

FIRE RISKS WITH TURBINES.

During the past two or three years there have been many serious fires in turbine installations owing to the accidental ignition of hot lubricating oil. Such fires have occurred on both sides of the Atlantic, and attention has been concentrated upon the means of eliminating this very serious hazard.

Oil pipes have been run in close proximity to, or across, pipes carrying steam at high pressure without any thought that this involved a fire risk. In many governor gears the steam control valve is oil-operated, the oil piston being situated above the steam chest. With the increasing temperature of steam the valve chests, etc., are at such a high temperature that when hot oil impinges upon them there is a serious danger of spontaneous ignition. The introduction of the oil-operated governor gear, many years ago, resulted in a very great simplification of the turbine; but it now appears that the oil side must be separated entirely from the steam side, and possibly some non-inflammable liquid used for actuating the governor mechanism.

Remedies that have been suggested vary according to whether it is a question of a new installation or of modifying an existing installation to reduce the fire risk. In new installations many precautions may be taken, including the placing of the oil pumps and tanks in a separate building from the turbine, running oil pipes from the pump to the lubricating system and to the governor system separately, so that they may be closed remote from the turbine, running these oil service pipes in outer drain pipes so that no leakage shall occur in the neighbourhood of any hot parts, the substitution of extra-heavy gauge fittings for the standard fittings that have previously been used, the use of oil pipes of a very heavy gauge, with welded joints, instead of the usual unions or flanged joints, and special precautions against vibration of oil pipes. Where it is impossible in existing plants to separate entirely the steam and oil pipes, then the steam-pipe insulation should be provided with metallic covers so that any leakage of oil cannot saturate the insulation and so render ignition easier. All oil piping should be so run that it can be inspected with facility, and wherever leakage is likely to occur, as at oil-coolers and pumps, drip pans and drains should be arranged to lead the oil away from any hot part. Oil tanks under or adjacent to the turbine should be arranged for rapid draining to some remote and safe position. In addition, for both old and new plants, adequate fire-extinguishing precautions should be taken.

MERCURY TURBINES.

Mercury turbines are still in the pioneer stage, although the experiments are on a large and instructive scale. In the last review mention was made of two 20 000-kW units then under construction: these are both working satisfactorily now. The author was very impressed by the Kearney 20 000-kW set when he saw it at work recently. Perhaps the most striking features are the necessarily great precautions taken to guard against the escape of mercury, owing to its toxic effects.

In the Kearney plant the turbine is on the highest floor of the building and above the mercury condenser, which, in turn, is over the mercury boiler. With this arrangement the liquid mercury flows by gravity to the boiler and the gaseous mercury rises naturally to the turbine, thus eliminating the mercury feed-pumps. The Kearney unit was first on load on the 27th March, 1933. Certain mercury-boiler troubles were experienced which put the unit off load, but up to the 1st July, 1934, it had been in service 56 per cent of the time; and during 11 034 hours had generated over 82 000 000 units, the capacity factor being just under 40 per cent.

In a plant of similar capacity at the makers' works at Schenectady, mercury pumps are used and the whole plant is approximately on one level and out of doors. The mercury feed-pumps are of the centrifugal type and have been most successful. The Schenectady unit supplies steam to the works, and the operation has been in the hands of the local utility company since the 1st December, 1933. It has been running at a regular day load of 16 000–19 000 kW, and no interruptions to service have occurred due to the mercury cycle. Up to the 1st July, 1934, it had generated about 32 500 000 units in 5 976 hours, a capacity factor of 27·1 per cent, and had been in service 56·6 per cent of the elapsed time since the first start on the 25th October, 1933. The older 10 000-kW set at Hartford is still going well. During the last completed year it was in service 94 per cent of the time, and the capacity factor was 65 per cent.

Of the mercury cycle it may, apparently, be said that the anticipated technical difficulties have been met and mastered. The mercury-steam binary cycle has received a lot of consideration, and data have been published showing that the heat consumption per unit may be brought down to 8 600 B.Th.U. This is an attractive figure in itself, but it is hindered at present by high capital charges, so that the mercury cycle is not yet likely to extend in popularity. Other materials have been considered for use with steam in a binary cycle, such as diphenyl, diphenyl oxide, zinc ammonium chloride, and aluminium bromide, but mercury still appears to be the best one.

In support of the steam cycle it may be pointed out that in the latest Thermal Returns of the Electricity Commissioners it is reported that the annual thermal efficiency of the new power station at Liverpool (Clarence Dock) is 26·06 per cent.

ALTERNATORS.

Size of Unit.

As to magnitude, the American 160 000-kW single-axis unit operating at 1 500 r.p.m. remains the largest. In Great Britain a unit of 100 000 kW is now being erected, and this will be the largest outside the United States. Many engineers remain unconvinced of the practical advantage of such units as compared with those of 50 000 kW at the same speed (1 500 r.p.m.). A 30 000-kW set working at 3 000 r.p.m. is an accepted size in Great Britain which presents some claim to recognition against larger units working at half the speed.

If there were any demand, many builders would be prepared to supply units with ratings of at least 200 000 kW at 1 500 r.p.m. The productive capacity is ahead of the demand, and the limiting features are transport and overall cash efficiency. One builder states that an 80 000-kW alternator running at 3 000 r.p.m. with aluminium rotor windings is a machine regarding which he would anticipate no difficulties; another has the same limit, but without the aid of aluminium. A unit of 80 000 kVA, 3 000 r.p.m., is at work near Antwerp.

High-Voltage Generators.

Generation at 36 000 volts has been adopted in several stations, one installation of three 20 000-kW units being as far from home as Cape Town. High-voltage generation does not appear to have been developed very greatly outside Great Britain, where one of the several builders has over 250 000 kVA installed or on order. There are some alternators working at 22 000 volts in the United States, but Continental builders do not report any high generation voltage.

Ventilation, Cooling, and Design.

The closed air cooling system is usual. In Germany, condensate is used for cooling as much as circulating water, but in Great Britain the coolers are generally on a shunt across the condenser circulating-water system.

As a further precaution against fire, although a closed system is in itself a safeguard and is regarded by many engineers as sufficient, some Continental engineers arrange for CO_2 to be admitted automatically into the system. This latter feature is perhaps applied more to hydraulic power stations.

A small development of the ventilating system is to be recorded in the total enclosure of the exciter, exciter slip-rings, and fan motors. Dust from the exciter brushes is extracted by filters before the air is returned to the main ventilating fans for cooling and re-circulation.

No progress has apparently been made with the use of hydrogen for the cooling of alternators. This has been used for synchronous condensers operating out-of-doors for a number of years. Manufacturers suggest that, if the out-door generating stations materialize, hydrogen cooling with totally enclosed units might then be adopted more generally.

There is a constant struggle here, as in other branches of engineering, to get a higher output per pound of material and to reduce losses. The use of silicon steel, containing up to 4½ per cent of silicon, has resulted in comparatively low losses. Such material presents some shop difficulties owing to low ductility, and a special technique has had to be developed. Stator casings and bedplates are usually welded now, with a saving in weight and a more rapid construction. Non-metallic and non-magnetic end-shields to reduce stray losses are now becoming standard. Some builders report that with the resulting increased efficiencies, the amount of air circulated for ventilation can be reduced, with a cumulative effect upon the efficiency.

The air coolers are placed under the unit generally, but for some large units the coolers and fans have been incorporated in the side yokes of the alternator on the main floor level. When this is done, a step-up transformer may be mounted in the foundation directly under, and connected solidly to, the alternator.

Quite recently, owing to the coming of the grid, alternator builders have been called upon to furnish machines having a considerable capacity for line charging at zero leading power factor. The usual requirement appears to be a capacity of 30 per cent of the normal output of the alternator. This may affect the future trend of design of alternators.

In one location evidence was produced showing that an air-insulated generator may become a practical possibility in the future, but probably not in the near future. Those concerned spoke of generating direct current at voltages of 300 to 400 kV. This would, if established, introduce a considerable change in generation and transmission.

CONDENSING PLANTS.

GENERAL.

There is little change to report in this section of the station equipment. There is no increase in the size of the individual shell, as multi-exhaust turbines are increasingly popular. In some cases the two exhausts are led into a single-shell condenser. Naturally the vacuum has not varied greatly, owing to natural limitations, but there is a tendency to specify a vacuum of which the temperature is perhaps only 21 deg. F. over the inlet temperature of the circulating water. A difference of from 23 to 24 deg. F. would in most cases probably give a higher overall efficiency.

CONDENSERS.

Cast iron is still used, but the welded-steel condenser is very popular. With these, cast-iron water heads are usually, but not universally, provided. Single-pass condensers remain the favourite in America, but not in Great Britain nor on the Continent. The conditions favourable to single-pass condensers are: (i) An ample supply of water. (ii) A low pumping head. (iii) Sufficient room for a long tube condenser. The first two conditions are to be found in those American stations situated on the Great Lakes or on some of the larger estuaries and rivers, and this may account for their greater use in America. Although a number of condensers are now supplied with hinged doors and divided water circuits, so that half of the water surface can be cleaned while the condenser is still in operation, it is still a little doubtful whether very great use is made of this feature. If there is a spare set in the station it appears probable that this will be used whilst the condenser is entirely cleaned.

TUBE VIBRATION.

Little is now heard of tube vibration, and probably it has been largely overcome. In addition to having a fine clearance in the holes of the supporting plates, uneven pitching of these plates has been found beneficial.

AIR EJECTORS.

Air ejectors are always of the steam-jet type, and except in very few cases have surface inter- and after-condensers. Except for vacua below 29 in., 3-stage ejectors are generally used owing to the lower steam consumptions. Large-capacity starting ejectors are occasionally fitted to evacuate the system when starting from standing.

AIR LEAKAGE.

The deleterious effect of air is well known, and plants are now very airtight. De-aerators are not much used. It is now realized that a pot of paint is worth as much as a de-aerator.

In Great Britain it is the established practice to install air extractors having a dry air capacity of 1 lb. per 2 000 lb. of steam handled in the condenser. It is admitted that the greater part of the air is leakage air, and therefore this basis is not really correct. The result is, however, that the extractor capacity is ample, and the vacuum under adverse conditions is not limited by lack of air-extraction capacity. Accurate test details have been published showing that the actual leakage is not more than 25 per cent of the amount for which the plant is designed, but no reduction in the capacity is suggested.

Tubes expanded at both ends are sometimes used to prevent water leakage either with a flexibly mounted plate, or, as this may leak, with the tubes bent into an arc by means of intermediate tube-support plates.

The use of separate and specially designed air coolers still seems to be confined to one firm. This is surprising, having regard to the special designs of air coolers which are recognized as requisite in the ventilating plant of the alternators and for use in conjunction with turbo-compressors.

CONDENSATE TEMPERATURES.

As at the time of the last review the condensate temperature had already reached the vacuum temperature and was claimed in some cases to be slightly above it, there is no progress to report. Tube arrangements are designed either to give the steam direct access to the bottom of the condenser or to interpose only a few rows of tubes in the anticipated path of the steam. This is done by steam lanes, by arranging the tubes in a concertina design, by having the air suction coincident with the axis of the condenser, by inverting the condenser, taking the steam round the tube nest and extracting the air at the top, or by some other device.

ATMOSPHERIC EXHAUST VALVES.

There is a distinct tendency for the size of the atmospheric exhaust valve to be reduced until it becomes, relatively speaking, merely a whistle. In conjunction with this small valve there is a trip gear which reduces the steam admitted to the turbine as the vacuum fails. Whilst this has been tried by a few builders over a number of years, it has not been generally accepted until quite recently as a satisfactory alternative.

DE-AERATORS.

These are rarely fitted now, as condensate is so well freed from air at the base of the condenser with the latest form of hot-well. Whether this is sufficient for pressures of 1 000 lb. per sq. in. and over is perhaps doubtful.

SWITCHGEAR

GENERAL DESIGN AND LAY-OUT OF MAIN SWITCHGEAR.

The tendency in power-station switchgear practice is keeping pace with the general movement towards larger and more efficient units. The busbar voltages in power stations are being raised, the practice being apparently to maintain the busbars at the highest system voltage wherever possible. This is not alone occasioned by the higher unit output in generators demanding a higher generating voltage in preference to a continued increase of copper section in the windings, but is also influenced by system conditions; and it has the useful result of reducing the maximum energy which can be fed into any fault in the system.

Modification in switching apparatus has resulted because the extra-high-voltage designs and equipments which were appropriate to transformer and switching stations and to the needs of transmission and interconnection do not fully meet the more exacting requirements of a power station as to safety, flexibility, and ease of control and maintenance. The effect in this country is consistent with the outstanding characteristics of British switchgear, as evidenced in years gone by, and the latest practice shows us factory-built mechanical unit switchgear of the metal-enclosed insulation-filled pattern. One departure from early lines is noticeable, however, in that isolators and selectors are now enclosed and the air plugging isolator disappears at the highest voltages.

The one-time evident tendency to produce elaborate busbar schemes with various alternative transfer routes for the switching of generators, transformers, and feeders, has given place to the plain duplicate busbar arrangement, generally with the main busbars sectionalized and the auxiliary busbars continuous. In large stations it is not unusual to find duplicate circuit-breakers in the more important circuits, instead of selectors to the main and auxiliary busbars. The use of individual step-up transformers with generator units is also eliminating the need for artificial reactance to limit short-circuit currents, and in general the reactance of essential apparatus is being arranged, both in position and in magnitude, to safeguard the system in respect of fault limitations and maintaining the voltage in sound sections.

There is now in operation at Tongland, in the South Scotland area, an installation of 132-kV metalclad gear. As compared with open-type switchgear, a considerable saving of space is effected which serves to offset any increase in the cost of the gear. The absence of exposed porcelain (which in open-type switchgear requires periodical cleaning) is an advantage, especially in industrial areas.

MAIN CIRCUIT BREAKERS.

The peaceful extinction of an a.c. arc produced in an oil circuit-breaker depends upon the rapidity with which the ionized gases that linger between the contacts during the zero-pauses can be de-ionized or rendered non-conductive to prevent re-establishment of the arc. De-ionization is essentially a process of ultra-rapid cooling, and is best accomplished by the arc itself producing from the oil relatively cool gas, which is then injected with considerable pressure and turbulence into the ionized gases.

For circuit breakers rated up to, say, 15 kV this is, possibly, done most economically by plain-type contacts within strong tanks. For higher-voltage ratings associated with relatively lower short-circuit currents it is economical to accelerate the de-ionizing process by individually enclosed contacts.

There is a movement in some quarters towards a reduction in the amount of oil used, and this development is parallel with the increasing use of arc-controlling devices. This reduction of oil content results, to some extent, from Continental exploitation of oil-less circuit-breakers, namely gas-blast and water breakers. These types are steadily displacing oil circuit-breakers in Germany, because the very serious attitude taken up by the insurance companies towards oil fire risks has virtually forced the oil breaker out of certain markets. British interest has been aroused to some extent in these oil-less circuit-breakers, but it is of a more casual nature because experience with oil breakers has not occasioned any active disquiet on the part of underwriting interests. Complete enclosure of switchgear conductors in earthed metal casings has doubtless gone a long way towards preventing disastrous breakdown, and this feature is of such outstanding importance that English manufacturers are loath to adopt new types of breakers which cannot be readily adapted to metal-enclosed gear.

Much interest has been aroused amongst designing engineers by attempts to find a non-inflammable arc-quenching device of high insulation value, or to render the oil used non-inflammable. Partial success only has been achieved so far, but there is ground for hope that progress in this line of endeavour may be shown in the future.

Changes in circuit breakers are more noticeable in regard to the current-carrying parts than the operating mechanisms, though in compressed-air breakers it is natural to find pneumatic operating gear. The speed of operation, however, is increasing, thus reducing the amount of energy liberated in the breaker when operated, and at the same time improving the system conditions by cutting down the amount of disturbance involved by a fault and helping to maintain stability.

TESTING STATIONS.

There are now two test stations in Great Britain for dealing with circuit breakers of the larger size, one of these being at Manchester and the other near Newcastle. A third one is understood to be under construction. The plant in the Manchester test station comprises a generator having an output of 1 500 000 kVA, based on the first half-cycle symmetrical current. Three-phase step-up transformers of full capacity are included, so that testing can be carried out at any standard voltage from 6 600 to 132 000 volts. The plant near Newcastle, which has been in regular operation since April, 1930, now has two generators that can be run in parallel, each with an output of 1 500 000 kVA asymmetrical on the first half-cycle, and it is therefore the most powerful and comprehensive in the world. It is completely equipped with step-up and step-down transformers, which enable tests to be carried out of apparatus rated at any voltage up to 220 000 volts. It is interesting to note that on the low-voltage side the plant is capable of giving currents up to 300 000 peak amperes at voltages up to 1 500 volts. These testing stations will doubtless enable British manufacturers to obtain more exact information regarding the performance of their products under the most severe conditions, information which previously was only obtained with difficulty owing to the necessity of not interrupting the supply when tests were made in any power station.

PROTECTION.

Differential protection is adopted where complete discrimination and instantaneous operation are demanded; other devices compromise in one feature or another where economical or other conditions limit complete freedom of choice. For stand-by and certain other protective duties, it is noticeable that the use of phase-sequence devices is gradually assuming the position of a recognized standard.

As a result of overhead-line systems there is being shown an increased interest in lightning protective devices, and their use is likely to be more extensive in future than it has been in the past.

Control and Supervision.

Power-station switchboard control has seen few striking developments. The use of miniature instruments and apparatus in order to conserve space in control rooms where a large number of circuits are being handled is more popular in the U.S.A. and the Continent of Europe than in England, where, however, there is a growing tendency to use them. Automatic diagrams for indicating the state of the electrical circuits have remained comparatively simple in this country, as compared with the spectacular elaboration which has characterized certain installations elsewhere. Control boards and desks have been improved in quality, these now being made almost exclusively of steel panels and completely enclosed so that the apparatus mounted therein is protected from dust and dirt. Wiring accommodation has also been improved, and circuits may now be readily traced.

The working of the grid has occasioned extensions to the applications of telemetering for the proper supervision of load distribution and control, but remote operation of the apparatus itself has not yet been carried very far.

Auxiliary Switchgear.

Auxiliary switchgear has naturally increased in capacity and complexity with the larger units and power stations, and there have been cases of more than average difficulty in providing adequate making and breaking capacity at the low voltages usual in auxiliary apparatus because of the extremely large normal currents and correspondingly greater fault currents.

Fortunately, in the limit the growth of station capacity finds its own solution automatically, as the conditions allow of distribution within the station premises at, say, 3 000 volts instead of 440 volts. There is thus afforded the possibility of operating the heavier auxiliary apparatus directly at 3 000 volts, and the smaller circuits are automatically protected by the reactance of the additional step-down transformers which are required.

As to the gear itself, it is noticeable that the metal-enclosed construction is proving itself most suitably adapted to the needs of this service, and few switchboards of other than this form are being installed. The heavy cost of providing oil-circuit breakers for all the consuming devices employed has given some impetus to the study and design of heavy-duty fuses, despite their relative inflexibility.

TRANSFORMERS.

Output.

During the last three years the number of large transformers has steadily increased, the largest transformers in the world have been built, and the largest transformers connected to the British grid have been installed. The two 93 750-kVA 33-kV 3-phase O.F.W.* transformers installed at the Barking power station are the largest for any system of cooling. The 75 000-kVA 132/33-kV 3-phase O.F.B.† transformers installed at Dalmarnock have each an O.N.‡ rating, in accordance with B.S.S. No. 171–1927, of 50 000 kVA. They are believed to be the largest naturally-cooled transformers in the world. The single-phase transformer units with a capacity of 20 833-kVA, forming 62 500-kVA 3-phase groups, installed at the Portishead station (Bristol) in 1929, remain the largest of their type.

Voltage.

The voltage of the British grid is 132 kV, and no occasion has arisen for the building of power transformers for higher voltages for home use. Transformers for circuits of 154 kV have been built by British makers for use in Canada.

Voltage Regulation under Load.

The provision of on-load tap-changing gear has extended rapidly during the period under review, until nowadays most large transformers are equipped with it. The methods in use are the parallel winding, the tapped reactor, and the bridging resistance, depending upon which is thought most suitable by the manufacturer concerned.

In a number of instances supply authorities have installed gear for voltage-changing under load, for the regulation of their existing distribution systems, without necessarily at the same time installing further transformers.

Protection against Surges.

The question of protection against lightning and other surges has received considerable attention. Several firms have equipped high-voltage laboratories and are prepared to carry out impulse tests. The design of transformers to withstand surges has been and is being carefully studied; and shields, static end-rings, and surge absorbers, have been used for the purpose of affording additional extraneous protection.

Efficiency.

The static transformer has still the highest efficiency of any piece of electrical machinery. The largest transformers have an efficiency as high as 99·3 per cent. Designs with lower efficiencies can be made with correspondingly lower capital cost. The economics of each case may be analysed by comparing the saving in capital cost with the capitalized value of the extra losses corresponding to the lower efficiency. This, however, is a subject on which, while much has been written, little has been standardized.

Minimization of Noise and Vibration.

Considerable attention has been given to the reduction of noise and vibration in transformers, and an elaborate study of the noise emitted by large transformers has been made, utilizing a microphone, amplifier, analyser, and cathode-ray oscillograph. The chief methods that have been adopted with the object of noise minimization are: the use of low flux density in the core and yokes; careful building and adequate clamping of the core; rigid fixing of all tank fittings, while so designing the tank that its walls will not resonate; and installation in houses or chambers properly designed and built for the purpose.

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* Oil-immersed, forced oil circulation, with water cooling.
† Oil-immersed, forced oil circulation, with air-blast cooling.
‡ Oil-immersed, natural cooling.

BOILERS.

GENERAL.

With the advance in boiler pressures, it was anticipated that the usual type of water-tube boiler would have to give way gradually in favour of some new design. With the larger unit size and pressures of 1 400 lb. per sq. in., it was thought that the drums would become unmanageable, but the old design has proved very satisfactory. In the great majority of the high-pressure stations the usual drum type of water-tube boiler with natural circulation has been used. It has done so well that many engineers in America are trying to install one boiler per turbine, even though the capacity of the latter in kilowatts is expressed in six figures. It is reported that reliability factors of 90 and 95 per cent are becoming possible, thus equalling the best performance of turbines.

Despite the excellent performance of the old type of boiler, the newer "evaporative" types have made some progress. Mention will be made of three of these —the Benson (not strictly an "evaporative" type); the Loeffler; and a new-comer, the Velox.

WATER WALLS.

The use of water walls is increasing very considerably and they are being supplied for boilers with an evaporative capacity as low as 30 000 lb. per hour. The wall system is now generally tied in with the main boiler circuit and does not, as originally, form part of a separate circuit leading direct to the steam drums.

CHAIN-GRATE STOKERS.

With the increased use of water walls, fuel consumption per sq. ft. of grate surface has increased very considerably and at the same time the stokers are attaining formidable dimensions. They are now made in widths up to 30–33 ft. and in lengths of 20–22 ft.

PULVERIZED FUEL.

There is little change to record in the position regarding pulverized fuel beyond that included in the previous review. On account of the dust trouble (see page 297) there is a tendency for solid fuel to be preferred in large towns, but it is claimed that pulverized-fuel installations have a considerable advantage owing to their great flexibility.

EMBRITTLEMENT OF STEEL.

Investigation and research appears to have elucidated the causes of this trouble and to have indicated the remedies. It appears to be due in the first place to the action of sodium hydrate on steel which has been heavily cold-worked or is subject to live stresses causing distortion in the metal, and secondly the subjection to continuous stress over a long period of material which is high in nitrogen content and has been cold-worked and subjected to a temperature such that the nitrogen is brought out of solution.

To guard against the second cause is comparatively easy; the nitrogen contents are reduced to a condition such that super-saturation could not occur. The cure for the first cause is not so simple. A solution of sodium hydrate would be harmless in a vessel with an entirely smooth interior, but not in a vessel which presents nuclei for a concentration of sodium hydrate, such as riveted seams, tube seats, or surface imperfections. Embrittlement can be prevented by the use of a suitable inhibitor such as sodium sulphate, and experience indicates that 3 parts of inhibitor are required to 1 part of sodium hydrate.

CONTROLLED SUPERHEAT.

With steam temperatures of 850° to 930° F., and in one case 1 000° F., at the turbine, the temperature at the boilers is approaching a figure at which the performance of the material becomes a matter of utmost importance. With lower steam temperatures a fluctuation of perhaps 100 deg. F. in the steam temperature at the boiler was not a matter of the utmost importance, but such variation cannot now be accepted, and consideration has been given to the best means of maintaining a constant upper temperature.

One firm has introduced a device called an "attemperator." This is a tubular vessel fitted either between two superheaters in series or after a single superheater, and in which the tubes are covered by feed water. Should the temperature exceed the limit a throttle valve is closed by thermostatic action, and the steam is diverted through this chamber. The feed water cools the steam to the predetermined temperature, and the heat is returned to the boiler drums in the form of steam. In the Loeffler boiler the same result is obtained by controlling the speed of the steam pump, passing more steam through the superheaters to reduce the temperature, and vice versa.

DRUMS.

Up to about five years ago riveted drums were used for pressures of about 700 lb. per sq. in., but there was always some doubt as to the effective closing of the long rivets required for the thick drums. Since then, forged drums have been used very largely. These are naturally very expensive, as the weight of the finished drum may be not more than about 40 per cent of that of the ingot from which it is made.

Great consideration has been given to the welding of drums, and it is now possible to weld satisfactorily up to 4¾ in. in thickness. This figure is really only limited by the plate-bending rolls available, and by the X-ray plant for examination of the complete weld. A welded steam receiver of large capacity has already been installed in Great Britain, and provided that there was a properly authenticated code dealing with the design and construction of such drums there would appear to be no reason why they should not become more generally used for boiler purposes.

BENSON BOILER.

This has been known for a long time as a critical-point boiler, and it was thought to be essential that evaporation should take place at the critical point without change of density so that ebullition surface was not needed. It has been demonstrated in Germany that this is a fallacy, and that the boiler works quite well at lower pressures. In this development the major part of the water heating is done by high-temperature radiant heat, but the actual evaporation is done in a part of the boiler where the furnace temperature does not exceed 1 400° F. The steam, slightly superheated, then passes back to the higher-temperature region and is superheated as required. This method allows the pressure to be as low as 450 lb. per sq. in.

It is seriously suggested that such a boiler in conjunction with a turbine designed for a pressure varying from 2 500 lb. per sq. in. at 100 per cent rating downwards represents an ideal combination for varying loads. Any speed variation in the turbine would act, not on the steam admission valve, but on the fuel and air supply to the boiler, and so vary the steam pressure to suit the load. Theoretically no turbine valve gear is needed, but in practice an emergency stop-valve would be essential to deal with a turbine overspeed; but the usual nozzle control valves could be eliminated. Another claim is that with the usual variation of vacuum with load, the adiabatic heat-drop remains almost constant. The relation between steam pressure and specific volume is such that, combined with this constant heat-drop, the volume of steam flowing is nearly constant at all loads. The turbine is therefore running with steam and blade velocities approximating to the design conditions, with some appreciable improvement in efficiency at partial loads.

This straight-line unit of boiler and turbine is being developed in America, where, up to now, boiler practice has been conservative, no boiler of any radical new type having been installed.

LOEFFLER BOILER.

This was also mentioned in the last review. It has made progress, and a new station in Czechoslovakia (Trebovice) is now at work with three such boilers each evaporating about 150 000 lb. per hour at a pressure of 1 850 lb. per sq. in. It will be remembered that in this boiler a centrifugal pump draws saturated steam from a drum and forces it through a superheater. The greater part of the steam then returns to the drum and evaporates saturated steam to supply the centrifugal pump. Between the superheater and the drum there is a connection from which steam is taken off for the turbines. The evaporation drum or drums are not exposed to the furnace temperatures, and in fact in the Trobovice installation these three drums are under the boiler-house floor in front of the boiler. The idea of a centrifugal pump handling steam was at first a novelty to most engineers, but it has proved to be a most reliable link in this system.

Some performance figures for Trebovice have been published, and they show, with two 20 000-kW turbines an overall heat consumption of about 13 000 B.Th.U. per unit delivered to the mains. A Californian station with two 100 000-kW units and gas-fired boilers of the usual type has reported almost exactly the same performance. With more experience and in a larger station, the Loeffler boiler may prove to be a very efficient and serious competitor to the older boilers.

VELOX BOILER.

There remains the Velox boiler, which has advanced from the experimental stage to a practical reality very rapidly. In the last review it was not mentioned. So much has been written recently concerning it, however, that no great detail need be given here. Briefly, the process is as follows. Compressed air, at about 35 lb. per sq. in., and gaseous fuel are forced into the boiler, which is so arranged that the velocity past and through the evaporating tubes is very high (450–900 ft. per sec.). The products of combustion, after passing through the superheater with a small pressure-drop, enter an exhaust-gas turbine, utilizing the remaining pressure-drop. They are then exhausted to the chimney through the feed-water heater. The gas turbine drives the air compressor which supplies the combustion air.

Unlike the Loeffler boiler, the Velox boiler is so arranged that evaporation takes place in the surface exposed to the highest temperatures, but the velocity of the water is very high, and the rate of flow is many times the rate of evaporation. The boiler is machine-shop-finished, and is very compact and light. Some 20 installations of this type are in hand or installed, including one to be made by a British firm for the British Admiralty. If the development of this boiler continues as rapidly as it has done in the past two or three years, it may become a serious competitor for small central-station work. It would appear to have great advantages where light weight and compactness are required, as for naval work. For central-station work, the idea of having the boilers in the turbine basement with the condensing plant is intriguing, and may not be an impossibility for small plants. As the Loeffler boiler deals entirely with the steam side of the boiler and the Velox boiler has modified the furnace side whilst hardly altering the steam side, it would appear possible that the two systems could amalgamate with advantage to both.

DUST AND SULPHUR.

Coming to general questions, one of the most alive is the trouble caused by fly ash, particularly in connection with pulverized-fuel installations. The Electricity Commissioners appointed a special committee to deal with this trouble, and their report has been published sufficiently long for action to have been taken. As a result, many of the large stations in Great Britain are building new chimneys about 300 ft. in height. Some stations are also installing an electrostatic system of dust precipitation, which has proved efficacious but expensive and bulky. Wet and dry separators are used in some places, and are reported to be satisfactory.

Of the sulphur trouble less has been heard lately. A large London station with an elaborate sulphur-elimination plant provides a pleasant sight with a large volume of vapour replacing the old-time smoke at the stack top.

Mention must be made of a large Australian station, Yallourn, inspected by the author. Here brown coal containing 66 per cent of moisture is burned. Many trials of various methods of drying were made, but eventually supplementary inclined grates arranged as an extension to the front portion of the travelling grate were installed. Inspection of the furnace showed distinctly that no combustion was occurring on the front portion. Another boiler house seen by the author is that at Long Beach, near Los Angeles. This is gas-fired, and the absence of dust, dirt, and fumes, is very obvious to one accustomed to coal-fired stations.

GENERAL.

Outdoor Power Stations.

Mainly with the object of reducing capital costs, the erection of plant entirely out-of-doors has been considered and to some extent tried. Rotary synchronous condensers, generally hydrogen-cooled, have been in use for many years, and as they were necessarily totally-enclosed they were naturally placed out-of-doors. The Benson boiler at Langerbrugge and the mercury boiler at Schenectady are also outside. Many waterfall generators in America are in the open, and even in Sweden a new power station for the Royal Board of Waterfalls is only provided with a cover for the control gear and operators. As America can show plant out-of-doors that has worked well between temperatures of about 100° F. down to nearly 30° F. below zero (or down to −35° C.) there is no reason to anticipate trouble in the Swedish installation, but when this is done what has been saved? Allowance will probably have to be made for cranes and certainly for offices and stores, so that the saving in building costs will not be more than 2 per cent of the whole installation cost. If necessary, steam turbines could be made suitable for working out-of-doors. Hydrogen cooling is usually associated with outdoor plant, but there is no reason why it should not be used in the normal station; it allows a higher rating from the same frame, and increases the operating efficiency.

Oil-Engine Power Stations.

Little need be said about the use of large oil engines in central power stations. Perhaps the most noteworthy installation which has been started recently is that at Vernon, near Los Angeles. This is a comparatively small industrial township situated in the area supplied by a large power company. Not being satisfied with the rates at which power could be purchased, the municipal authorities started a 35 000-h.p. oil-engine power station and are supplying power to a compact industrial area. With a good load factor and a small distribution area, this station is doing very satisfactorily. Another oil-engine station of some magnitude is the Montemartini station at Rome, where two 5 000-kW oil engines running at a speed of 150 r.p.m. are installed. The normal frequency is 45 cycles per sec., and it is rather remarkable to note that a non-standard frequency is being perpetuated.

Peak-Load Plant.

There has been no great development in this direction. So long as the operating conditions are ever advancing, engineers will probably continue to use the older units to meet the peak loads, reserving the base load for the latest installed units. If ever steam conditions become static, it is probable that special consideration will be given to producing turbines more suitable for the high loads required during only a few hours in the year: turbines which would be less efficient and therefore cheaper to install.

There has been some development in the use of steam-accumulator schemes. The Charlottenberg installation has now been at work for some time, and good reports regarding it have been received. Its technical ability to function satisfactorily was never seriously doubted, and only full details of the capital cost, together with the performance, would enable the suitability of the installation to be assessed. An accumulator system for the peak load in a central power station is an entirely different proposition from meeting a more frequent cyclical peak in an industrial works.

It is considered by many that the correct and cheapest method of providing for peak-load capacity is to install turbine sets with a maximum output very much greater than the usual 25 per cent in excess of the most economical rating.

Closely allied with peak-load plant is the hydraulic storage of power through electrically-driven pumping stations. Whilst this type of plant may be used to correct seasonal variations in the supply of water power, it may also be used for meeting the daily load fluctuation in a system dependent upon thermal stations, and particularly is this possible when the transmission can be provided at a small extra cost, as when the existing transmission lines can be partially utilized. A fair-sized station of this type has recently been set to work at Sillre, in Sweden. On a vertical axis there is an electric machine (motor or generator as required) with a capacity of 7 000 kVA, a Francis turbine of 9 330 h.p., and a centrifugal pump; the head is 190 metres.

Conclusion.

Once more the author wishes to record his thanks to the many engineers connected both with the manufacturing and with the operating side of the power station industry in the United Kingdom, France, Germany, Switzerland, America, Australia, and Czechoslovakia. A large amount of information has been received; more, in fact, than could be included in a review of this nature.

COPPER LOSSES IN LARGE CABLES AT POWER FREQUENCIES.*

[REPORT (REF. F/T55) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

(*Paper received* 13*th July*, 1934.)

SUMMARY.

An experimental investigation of the copper losses in large cables when carrying alternating current at power frequencies has been carried out at the National Physical Laboratory. Measurements were made with single-phase current on two parallel cables, of equal length and section, forming lead and return. Six pairs of cables of four different cross-sectional areas were tested. The strands of four of these pairs were enamelled, so that the current was compelled to follow the strand. The strands of the remaining two pairs of cables were uninsulated, so that the current was free to flow from strand to strand. The sections of the cables tested ranged between 0·7 sq. in. and 1·9 sq. in., and the range of frequency covered was 25 to 100 cycles per second.

The measurements showed that the effective resistance (copper losses/current^2) of the cables with enamelled strands was independent of the distance between the lead and return cables, and that its value could be estimated with an error not exceeding 1 per cent from the formula for skin effect for an isolated conductor of circular cross-section, which has been developed by Clerk Maxwell, Lord Kelvin, and others.

The measurements made on the cables with bare strands showed that the effective resistance of conductors within the range tested was 1 or 2 per cent higher than that of the same sized cable with enamelled strands at the same frequency, and when the distance between lead and return cables was large. This small increase was due to the spiralling of the strands. Its magnitude is dependent on the lay ratio and on the degree of contact between strands, but it is so small, in even the worst case, as to be negligible for practical purposes. As the distance between the cables was decreased the effective resistance was observed to increase. This effect is usually known as the proximity effect, and the formulæ for its evaluation in the case of solid conductors of circular cross-section have been developed by Mie, Nicholson, Carson, Butterworth, and others. These formulæ, however, cannot be applied to the calculation of proximity effect in cables since the proximity eddy currents flow from strand to strand, and the resistances of these paths are not amenable to exact calculation, and are certainly different from the resistances involved in the solid conductor. The degree of contact between strands is probably a very important factor, and measurements on a number of cables would be required in order to establish what consistency could be expected.

The effective resistance of the largest cables with bare strands tested (1·9 sq. in.) varied from 110 per cent of the direct-current resistance at a frequency of 25 cycles per second to 132 per cent at 50 cycles per second, and 175 per cent at 100 cycles per second, when the lead and return conductors were far apart. When the lead and return conductors were close to each other the effective resistance was found to be 117 per cent of the direct-current resistance at 25 cycles per second, 155 per cent at 50 cycles per second, and 239 per cent at 100 cycles per second.

CONTENTS.

Nature of the Problem.
Skin Effect in a Straight Solid Conductor of Circular Cross-Section and in a Cable.
Experimental Work.
Experimental Results.
Conclusions.
Lines of Further Work.
Appendix I. The Measurement of Low Impedances of Low Power Factor with Alternating Current.
Appendix II. A Review of some of the Approximate Formulæ for Skin Effect in a Straight Solid Conductor of Circular Cross-Section and in a Cable.
Appendix III. Bibliography on Copper Losses in Solid and Stranded Conductors of Circular Cross-Section, excluding Conductors of Magnetic Material but including Papers on the Subject of Sheath and Armouring Losses in Power Cables.
Appendix IV. Tables for the Rapid Calculation of the Skin Effect in a Solid Conductor of Circular Cross-Section and in a Cable.

NATURE OF THE PROBLEM.

When a steady electric current flows in a conductor the current distributes itself across the section so as to give minimum dissipation of energy in the conductor. In a long straight conductor of uniform section, and of homogeneous material at a uniform temperature, this condition is realized by a constant current density across the section. The power dissipated in the conductor per centimetre length divided by the square of the current is defined as the direct-current resistance of the conductor per centimetre length and is denoted by the symbol R.

When an alternating current or a transient current flows in a conductor of infinite conductance, the current density is determined solely by the condition of minimum storage of energy (minimum inductance) in the electromagnetic field, neglecting dielectric currents.

In a conductor with finite conductance the current density is determined by the resultant of the two tendencies towards minimum electromagnetic storage of energy and minimum energy dissipation in the conductor, assuming that the dielectric current is negligible. In a long straight conductor of uniform section carrying a periodic alternating current of frequency f cycles per second, the mean power dissipated in the conductor per centimetre length divided by the mean square of the current is defined as the alternating-current resistance of the conductor per centimetre length at the frequency f, and is denoted by the symbol R'. The alternating-current resistance of a conductor is always greater than the direct-current resistance, and always increases as the frequency increases.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

An important principle put forward by H. B. Dwight (21) and proved by J. Slepian is given here.*

Principle of Similitude.

"If several systems of straight parallel conductors of uniform cross-sections, carrying single-phase or polyphase currents, have similar linear dimensions in a plane perpendicular to the conductors, then the ratio of alternating-current resistance to direct-current resistance per centimetre length, (R'/R), will be the same for corresponding conductors in each system provided that the ratio of the frequency to the direct-current resistance per centimetre length (f/R), is the same for all the systems."

For example, a 1-sq. in. conductor of given cross-sectional shape and resistivity would have the same value of R'/R at a frequency of 50 cycles per second as a 2-sq. in. conductor of similar shape and equal resistivity at a frequency of 25 cycles per second.

Alternatively, at a given frequency a 1-sq. in. conductor of given cross-sectional shape would have the same value of R'/R as a 2-sq. in. conductor of similar shape and twice the resistivity.

Therefore, in considering a particular system of conductors it may be said that $R'/R = \phi(f/R)$, where $\phi(f/R)$ is some definite function of (f/R).

The simplest system from a mathematical point of view is that of a single conductor of circular cross-section. It is usually assumed that the return conductor (or conductors) is sufficiently remote to have no appreciable disturbing effect on the distribution of current in the conductor under consideration. Alternatively, the return current may be assumed to flow in a concentric tubular conductor of any internal diameter greater than the diameter of the conductor considered, since in this case the return current will not disturb the current in the central conductor. The relation between R'/R and f/R for this system has been determined theoretically by J. Clerk Maxwell (3), O. Heaviside (4), Rayleigh (5), Kelvin (6), A. Russell (8), and others, and this relation has been verified experimentally, to an accuracy of approximately 1 per cent, by A. E. Kennelly, F. A. Laws, P. H. Pierce, and H. A. Affel (14 and 16).

In a conductor of circular cross-section the alternating current tends to concentrate in the outer layers of the conductor only, since the inductance of a tube is less than the inductance of a solid rod of the same diameter. This phenomenon has been termed "skin effect," since at very high frequencies the whole current in the conductor is concentrated in a thin outer layer.† Unfortunately, a number of writers have adopted the term "skin effect" to refer to the increase of resistance of a conductor with alternating current in any system. This is liable to cause a certain amount of ambiguity. In this report the "skin effect" of a solid conductor of circular cross-section is defined as the ratio of the increase of resistance with alternating current to the direct-current resistance, all other conductors being assumed to be sufficiently remote to have no effect on the current distribution in the conductor under consideration.

Another system consists of a single-phase circuit of two straight parallel conductors of circular cross-section, forming lead and return. In this case, in addition to the "skin effect" already referred to, there is an additional increase of resistance caused by a concentration of the current on the side of the conductor nearest to the return conductor, since this concentration reduces the inductance of the circuit. This effect is quite small when the conductors are far apart, but increases rapidly as the conductors are brought closer together. If the conductors are nearly touching, the effect may be nearly twice as great as the skin effect. This phenomenon is usually termed the "proximity effect." It is probable that the skin effect undergoes some modification as the conductors are brought closer together, but it is more convenient to assume the skin effect constant and to ascribe all change of resistance due to proximity of return conductor to the proximity effect.

In this report, proximity effect is defined as the ratio of the additional increase of resistance with alternating current to the direct-current resistance of a conductor, caused by the presence of other conductors carrying alternating current.

This definition is much wider in its scope than the definition of skin effect, and further subdivision of the "proximity effect" might be necessary in considering a complicated system of several conductors.

The theoretical determination of the proximity effect in the case of the single-phase system of two parallel conductors of circular cross-section is a more difficult problem than the skin-effect problem. Solutions have been put forward by G. Mie (7), J. W. Nicholson (9), J. R. Carson (29), S. Butterworth (30), S. P. Mead (38), and others. Butterworth shows that his solution gives results which are in close agreement with Kennelly's experimental results (14).

Systems of considerable practical importance consist of two or more straight parallel cables. The term "cable" is used in this report to denote a stranded conductor in which the strands are spiralled in opposite directions in consecutive layers, and any given strand is at a constant distance from the axis of the cable throughout its length.*

These systems are not so easily amenable to mathematical treatment as systems of solid rods, partly on account of the additional complication introduced by the spiralling, and partly on account of the indefinite nature of the contact resistance between strands. Some experimental work is therefore necessary in order to develop empirical formulæ for the alternating-current resistance of cables. The importance of the problem may be realized from the fact that the alternating-current resistance of a 2-sq. in. copper cable, capacity about 2 000 amperes, at a frequency of 50 cycles per second, may be 50 per cent greater than the direct-current resistance of the same cable; while at 100 cycles per second the resistance may approach two and a half times the direct-current value.

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* Bibliography 21. J. Slepian's proof is given in the discussion on this paper.

† Actually, the current density falls off rapidly from the circumference towards the axis of the conductor and at the same time undergoes a change of phase. Thus it may happen that the current at the centre of the conductor is flowing in the opposite direction to the current at the circumference, so that the removal of the central part of the conductor would reduce the resistance of the whole conductor. For the sizes of conductors and frequencies considered in this report, up to 2 sq. in. of copper at a maximum frequency of 100 cycles per second, the alternating-current resistance of a solid conductor is always less than that of a tube of the same external diameter.

* Conductors in which the strands are specially interwoven, so that the impedances of all the strands are equal, are not considered in this report. Formulæ for cables, which are given later in this report, are not valid for such conductors.

An experimental investigation of the alternating-current resistance of large cables at frequencies up to 100 cycles per second was therefore undertaken by the National Physical Laboratory at the request of the Electrical Research Association. The results obtained do not cover the whole ground, and useful lines of further work are indicated at the end of the report. Previous experimental work is very meagre. Kennelly (14) made some measurements on 7-strand cable at high frequencies, while W. I. Middleton and E. W. Davis (28) carried out measurements on large cables at frequencies up to 60 cycles per second. The accuracy of these latter results has been questioned by several American writers.

The problem in many respects is similar to that of a round rod, but differs from it in certain important points. Kennelly (14) deduced from theoretical considerations that the subdivision of a solid conductor into straight insulated filaments would not affect the alternating-current resistance. A stranded conductor with straight strands would therefore have the same alternating-current resistance as a solid rod of circular cross-section for equal values of the ratio of the frequency to the direct-current resistance per centimetre length (f/R). It is important to note, however, that at a given frequency and for a given material, a stranded conductor will have a larger diameter than a solid rod for equal values of f/R, on account of the air spaces between strands.

The strands in a power cable are spiralled, the spirals being in opposite directions in consecutive layers. This spiralling does not affect the skin effect appreciably, for whether the current follows the strands or jumps from strand to strand, it is still free to concentrate in the outer layers of the conductor. The experimental results described later show that the skin effect in a cable is practically the same as the skin effect in a solid rod for equal values of f/R. These results were obtained on cables up to 2-sq. in. section and for frequencies up to 100 cycles per second. On the other hand, the proximity effect in a cable is very different from that of a solid rod. In order that the current may concentrate on one side of the cable it is necessary for the current to jump from strand to strand, since the strands continually change their position relative to the return conductor. It is impossible to assess the resistances of the paths followed by the current. It is probable that in actual cases the current will follow the strand for short distances and jump from strand to strand only at points where the contact resistance between strands is very low. It may be expected, therefore, that the proximity loss in a cable will be appreciably less than in an equivalent solid rod.* The experimental results given later show that this is actually the case. The proximity loss in the case of the two cables tested was approximately half the value that it would be for an equivalent solid rod. An empirical formula is given later for evaluating the proximity effect in the case of the two cables tested. These cables, however, had no insulation or lead covering. It is almost certain that the insulation and impregnation of an ordinary power cable would lower the contact resistance between strands. The lay ratio would probably also be a factor affecting the magnitude of the proximity effect. Further work on standard cables would be necessary in order to deduce a satisfactory empirical relation for the proximity effect.

In addition to the skin and proximity effects, there is in cables an additional source of loss, which is usually termed the spirality effect. Some of the current flowing in the cables follows the strands, and thus produces a small longitudinal magnetic field in addition to the main transverse field. This longitudinal field sets up small eddy currents in the cable flowing from strand to strand at right angles to the main current flow. The effect was found to be quite small, involving an increase of resistance of about 2 per cent in the case of a 2-sq. in. cable at a frequency of 100 cycles per second. Its magnitude is dependent on the lay ratio and the contact resistance between strands, but it is so small in all practical cases that it may safely be neglected in assessing current-carrying capacity.

Thus, in the case of a cable, the alternating-current resistance may be divided into four components:—

1. The direct-current resistance.
2. The increase due to skin effect.
3. The increase due to spirality effect.
4. The increase due to proximity effect.

There is an uncertainty in the theoretical estimation of the direct-current resistance of a cable according to whether it is assumed that the whole current follows the strands or whether it is assumed that part of it jumps from strand to strand. W. E. Alkins (45) made some measurements on cables which indicate that the greater part of the current follows the strands. It is commonly assumed that the spiralling of the strands of a cable increases its direct-current resistance from 1 to 2 per cent according to the lay ratio. If it is further assumed that, as far as skin effect is concerned, the current still follows the strands, then the following simple definitions may be adopted for skin effect, spirality effect, and proximity effect, in cables.

The "skin effect" of a cable with insulated strands is defined as the ratio of the increase of resistance with alternating current to the direct-current resistance when all other conductors are at a considerable distance away. The ratio of the increase of resistance with alternating current to the direct-current resistance of a cable with uninsulated strands, when all other conductors are at a considerable distance away, consists of two parts, the "skin effect" and the "spirality effect."

The "skin effect" is that part which is equal to the "skin effect" in a cable with insulated strands for the same value of f/R. The "spirality effect" is defined to be the remainder. In other words, the "spirality effect" is the ratio of the additional increase of resistance with alternating current to the direct-current resistance of a cable with uninsulated strands, all other conductors being a considerable distance away, caused by eddy currents flowing from strand to strand.

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* An "equivalent solid rod" is defined as a straight solid conductor of circular cross-section having the same value of f/R as the cable under consideration. In comparing the proximity effects in a cable and in an "equivalent solid rod" it would also be necessary that the geometry of the two systems should be similar. Strictly, this is impossible, since the section of a cable is not absolutely circular, but when the number of strands is large the departure from circular shape is not great.

The "proximity effect" of a cable is defined as the ratio of the additional increase of resistance with alternating current to the direct-current resistance caused by the presence of other conductors carrying alternating currents.

SKIN EFFECT IN A STRAIGHT SOLID CONDUCTOR OF CIRCULAR CROSS-SECTION AND IN A CABLE.

Kelvin (6) gave the solution for the skin effect in a straight solid conductor of circular cross-section in the form given below, Equation (1). This is the form most commonly used, but the solution may also be given in terms of infinite series. The experimental results given later in this report show that this equation may also be used to estimate the value of the skin effect in cables for values of the independent variable, x, up to 4·2.

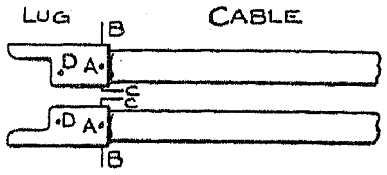

FIG. 1.—Potential points tried out.
A, A, adopted.

$$\text{Skin effect} = y = \left[\frac{\frac{1}{2}x\{\text{ber}\,x\,\text{bei}'\,x - \text{bei}\,x\,\text{ber}'\,x\}}{\{(\text{ber}'\,x)^2 + (\text{bei}'\,x)^2\}}\right] - 1 \quad (1)$$

where $x = \sqrt{8\pi f/(R \times 10^9)}$
f = frequency in cycles per second.
R = direct-current resistance of conductor in ohms per centimetre length.
R' = alternating-current resistance of conductor in ohms per centimetre length.

Ber x and bei x are respectively the real and imaginary parts of the ordinary Bessel function of order zero, J_0 having for its argument $xj\sqrt{j}$, where x is a real quantity. These functions are given by the series below:—

$$\text{ber}\ x = 1 - x^4/(2^2 4^2) + x^8/(2^2 4^2 6^2 8^2) - \ldots$$
$$\text{bei}\ x = x^2/2^2 - x^6/(2^2 4^2 6^2) + x^{10}/(2^2 4^2 6^2 8^2 10^2) - \ldots$$
$$\text{ber}'\,x = \frac{d}{dx}(\text{ber}\ x) \quad \text{bei}'\,x = \frac{d}{dx}(\text{bei}\ x)$$

In the cases of a solid rod with no other conductors near to it and a cable with insulated strands, the skin effect is the only effect increasing the resistance of the conductor, so that Equation (2) below may be used to estimate the ratio of the alternating-current resistance of the conductor to its direct-current resistance.

In other cases account must be taken of the spirality and proximity effects:—

$$R'/R = 1 + y \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For a conductor of resistivity $1{\cdot}724 \times 10^{-6}$ ohm per centimetre cube (copper) at 20° C.,

$$x = 0{\cdot}1207\sqrt{(fA)} = 0{\cdot}3066\sqrt{(fA')} \quad . \quad . \quad (3)$$

At the standard frequency of 50 cycles per second, Equation (3) reduces to

$$x = 0{\cdot}853\sqrt{A} = 2{\cdot}168\sqrt{A'} \quad . \quad . \quad . \quad (4)^*$$

where A = effective cross-sectional area of conductor in square centimetres, and
A' = effective cross-sectional area of conductor in square inches.

The effective cross-sectional area of a conductor is defined as the resistivity of the conductor divided by the direct-current resistance per unit length. The spiralling of the strands makes the effective cross-sectional area of a cable 1 or 2 per cent less than the actual cross-sectional area of the copper.

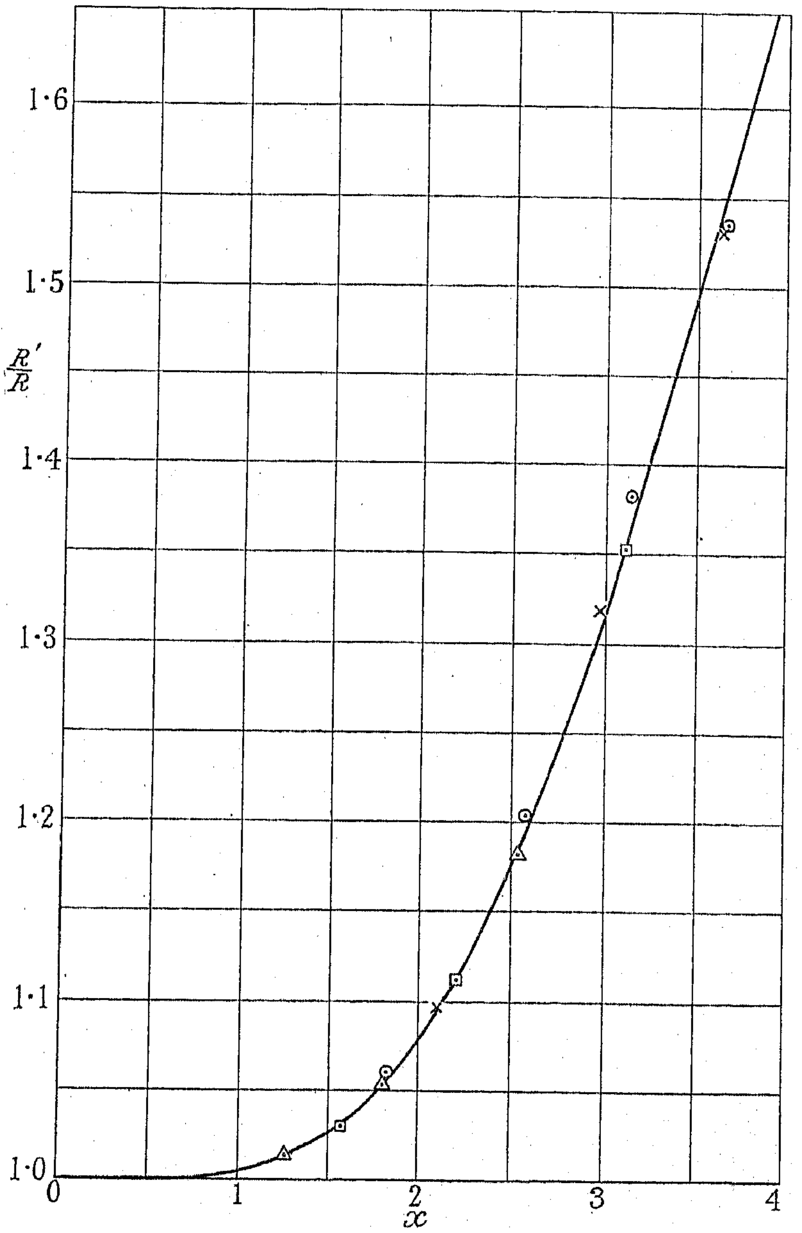

FIG. 2.—Ratio of a.c. resistance to d.c. resistance of cables with insulated strands (curve shows the value of R'/R obtained by plotting equation (2).

Experimental points for 1·87 sq. in. cable shown thus ×
" " " 1·41 " " " " ⊙
" " " 1·01 " " " " ⊡
" " " 0·68 " " " " △

The values of y, as given by Equation (1), are tabulated in Table 8 for values of x from 0 to 5 in steps of 0·01. The curve in Fig. 2 shows the variation of R'/R, as given

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[*] A rough relationship between x and A' for copper at a frequency of 50 cycles per second is $A' = \frac{1}{4}x^2$.

by Equation (2), with x. The experimental points obtained for cables with insulated strands are also shown in this figure. When x is less than unity, $y = x^4/192$ approximately. When x is greater than 5, $y = \frac{x}{2\sqrt{2}} - \frac{3}{4}$ approximately. At a given frequency and for a given resistivity, x is proportional to the diameter of the conductor, so that for a small conductor the skin effect is proportional to the fourth power of the diameter, while for a large conductor it is directly proportional to the diameter.

The validity of Equations (1) and (2) for evaluating the skin effect in solid rods has been verified experimentally to within 1 per cent by the work of Kennelly, Laws, Pierce, and Affel (14 and 16). The validity of these equations for evaluating the skin effect in cables has been verified experimentally to within 1 per cent, for values of x up to 4·2, by the work described in this report.

EXPERIMENTAL WORK.

Six pairs of copper cables were made up for this work by W. T. Henley's Telegraph Works Co., Ltd., each cable being 30 ft. long with a terminal lug soldered solidly to each end. The diameter of the strands was 0·120 in. in all the cables, and the lay ratio was approximately 13 for all the layers of strands in all the cables. This very small lay ratio was chosen in order to make the spirality effect the maximum likely to be encountered in practice. No insulation was wrapped round the cables. The sectional areas varied from 0·7 to 1·9 sq. in. Full particulars of the cable dimensions are given in Tables 3 and 5.

The strands of four pairs of cables were enamelled in order to prevent the current passing from strand to strand, thus avoiding the uncertainty due to indefinite contacts between strands. Since the insulation between strands suppressed both the spirality and the proximity effects, the measurements on these cables provided a direct check of the validity of Equation (1) for estimating skin effect. Tests carried out on these cables showed that the enamelling and laying-up of the cables had been carried out with such care that not a single contact between strands was found on the completed cables. The Association's thanks are gratefully accorded to W. T. Henley's Telegraph Works Co., Ltd., for this achievement.

The strands in the remaining two pairs of cables were uninsulated, and the tests carried out on these cables were intended to indicate the order of magnitude of the spirality and proximity effects. The results can only be interpreted with caution, since the contact resistance between strands may vary in different cables. Further work would be necessary in order to establish what consistency could be expected in practice.

The cables were tested in pairs, the two cables being placed parallel to each other on trestles, and reasonably distant from all metalwork which would be likely to increase the apparent power loss in the cables. Potential points were fitted to the lugs within a quarter of an inch of where the lug ended, so as not to include the resistance of the lug. Initial measurements showed that the ratio of R'/R was independent of the position of the potential point round the circumference of the lug. When the potential point was moved to the other end of the lug (see Fig. 1) a slight increase of R'/R was observed, which was probably due to proximity loss in the lug itself. The results are given below.

TABLE 1. (See Fig 1.)

Position of potential points	Measured value of R'/R	
BB	1·760	Mean value 1·761
AA	1·761	
CC	1·762	
DD	1·765	

The position AA was adopted throughout as being probably the most satisfactory position.

Six measurements were required for each reading.

(1) *The Overall Diameter of the Cable* (d).

The mean value of a number of measurements along the length of the cable was taken. This measurement was made to an accuracy of 0·1mm, or 0·4 per cent of the diameter of the smallest cable.

(2) *The Axial Distance between Lead and Return Cables* (s).

The outside or inside distance between the cables was measured by means of callipers at a number of points and the mean value taken, from which and from the diameter of the cable already measured the axial spacing was deduced. This measurement was made to an accuracy the same as or better than that of Measurement (1). The cables, which were never bent during manufacture or transport, were laid as straight and parallel as practicable. The maximum difference between the spacing of the cables at any point and the mean spacing of the cables was found to be about 2 mm.

(3) *The Length of the Cables between Potential Points.*

This measurement was made to an accuracy of approximately 1 mm, or 0·01 per cent of the length measured.

(4) *The Direct-Current Resistance of the Cable between Potential Points.*

Two potentiometers were used for this measurement. The current was held steady at a predetermined value by means of one potentiometer, while the voltage-drop between potential points was measured on the other potentiometer. The error involved in this measurement was less than 0·1 per cent of the resistance measured.

(5) *The Alternating-Current Resistance of the Cable between Potential Points.*

A special bridge was used for this measurement, which is fully described in Appendix I. The errors involved in this measurement were dependent on the power factor of the cable, and were less than 0·3 per cent of the resistance measured in the worst case.

(6) *The Frequency of the Alternating Current.*

The current was obtained from a generator, to the shaft of which was fixed an auxiliary three-phase generator. This auxiliary generator supplied a synchronous motor which was placed in a convenient position for observation. To the shaft of this motor was fixed a semi-transparent disc with eight black circles marked on it at equal distances from the centre and equally spaced. This disc was illuminated periodically by a neon lamp which was controlled by a 50-cycle tuning fork. Thus when the motor was running at a speed corresponding to a frequency of 50 cycles per second, the black circles appeared stationary. A small excess or deficiency of speed resulted in an apparent slow rotation of the circles in one direction or the other. The number of circles was chosen so that at frequencies of 25 cycles per second and all integral multiples of 25 cycles per second the spots appeared stationary.

TABLE 2.

Tests on Round Copper Rod.

Frequency, cycles/second	Length between potential points, cm	D.C. resistance between potential points, microhms	x	Computed value of skin effect, y	Computed value of proximity effect	Computed value of $R'/R = 1 + y$ + proximity effect	Measured value of R'/R	$\frac{\text{Measured } R'/R}{\text{Computed } R'/R}$
25	313·9	66·81	1·718	0·044	0·001	1·045	1·047	1·002
50	313·9	66·81	2·430	0·159	0·002$_5$	1·161$_5$	1·164$_5$	1·003
75	313·9	66·82	2·976	0·310$_5$	0·003$_5$	1·314	1·318	1·003
100	313·9	66·65	3·440	0·470	0·004$_5$	1·474$_5$	1·481	1·004
100	253·0	53·64	3·443	0·471$_5$	0·004$_5$	1·476	1·481	1·003
100	203·0	43·00	3·445	0·472	0·004$_5$	1·476$_5$	1·480	1·002
100	152·9	32·44	3·442	0·471	0·004$_5$	1·475$_5$	1·480	1·003
100	102·8	21·77	3·445	0·472	0·004$_5$	1·476$_5$	1·479	1·002
100	52·7	11·14	3·448	0·473	0·004$_5$	1·477$_5$	1·479	1·001

TABLE 3.

Particulars of Cables. (*Enamelled Wires.*)

Cable pair	Number of strands	Diameter of strands, in.	Effective cross-sectional area, sq. in.	Overall diameter		Length between potential points, cm
				in.	cm	
No. 1	169	0·120	1·87	1·890	4·80	903·1
No. 2	127	0·120	1·41	1·634	4·15	902·0
No. 3	91	0·120	1·01	1·378	3·50	904·4
No. 4	61	0·120	0·68	1·121	2·85	906·3

The method is extremely sensitive and has been in use at the Laboratory for routine work for many years. Its accuracy is limited only by the accuracy of the tuning fork. The tuning fork used for these experiments was calibrated and found to be accurate to within 0·1 per cent.

A very full range of measurements was taken on all the pairs of cables and the results obtained are given in Tables 4 and 6, and Figs. 2 and 3. From these, it may be seen that in the case of the cables with enamelled strands the measured value of R'/R agrees with the value obtained by computation from Equation (2) to within 1 per cent for any distance between cables except for a very small range when the cables are close together. In this range there is a small increase of R'/R, amounting in the worst case to less than 1 per cent.

It may be deduced from these results that the skin-effect formula for round rod [Equation (1)] may be applied to cables, with insulated strands, up to 2 sq. in. in section and up to a frequency of 100 cycles per second, with an error of less than 1 per cent. It may further be deduced that "spirality effect" and "proximity effect" are eliminated by the insulation between strands. A probable explanation of the slight increase in the value of R'/R when the cables are brought very close together may be found in the short length of cable tested. In a long length of cable the impedances of every strand in a given layer would be equal on account of the spiralling and, therefore, each strand in a given layer would carry equal current, and there would be no proximity effect. In the short length tested, where the length of the lay is not negligible compared with the length of the cable, the impedance of each strand in a given layer will not be quite the same, so that the currents in the strands in a given layer will be slightly different, thus increasing the value of R'/R. This increase of R'/R may be regarded as an error inherent in the condition of measurement, and it

TABLE 4.

Tests on Cables with Insulated Strands.

Cable pair	Overall diameter / Axial spacing $= d/s$	Frequency, cycles per second	D.C. resistance between potential points, microhms	x	Computed value of $R'/R = 1 + y$	Measured value of R'/R	Measured R'/R / Computed R'/R
No. 1 (169 strands) ..	0·0981	25	128·75	2·099	1·094	1·098	1·004
		50	129·00	2·966	1·307	1·318	1·008
		75	128·62	3·638	1·543	1·550	1·005
		100	128·36	4·205	1·754	1·755	1·001
	0·572	25	127·72	2·108	1·095	1·100	1·005
		50	127·72	2·981	1·312	1·322	1·008
		100	127·72	4·216	1·758	1·757	0·999
	0·970	25	127·72	2·108	1·095	1·102	1·006
		50	127·72	2·981	1·312	1·327	1·011
		100	127·65	4·217	1·759	1·777	1·010
No. 2 (127 strands) ..	0·0837	25	169·91	1·826	1·055	1·060	1·005
		50	169·92	2·583	1·196	1·205	1·008
		75	169·92	3·163	1·372	1·382	1·007
		100	169·50	3·657	1·550	1·556	1·004
	0·654	25	169·75	1·827	1·055	1·060	1·005
		50	169·76	2·584	1·196	1·206	1·008
		75	169·73	3·165	1·373	1·386	1·009
		100	169·67	3·655	1·549	1·559	1·006
	0·856	25	170·63	1·823	1·055	1·060	1·005
		50	170·63	2·577	1·195	1·207	1·010
		75	170·58	3·157	1·370	1·386	1·012
		100	170·53	3·646	1·546	1·564	1·012
No. 3 (91 strands) ..	0·1006	25	235·2	1·554	1·030	1·031	1·001
		50	236·0	2·194	1·110	1·113	1·003
		100	236·2	3·102	1·352	1·352	1·000
	0·978	50	237·2	2·189	1·109	1·115	1·005
		100	237·4	3·094	1·349	1·357	1·006
No. 4 (61 strands) ..	0·1587	25	355·1	1·266	1·013	1·014	1·001
		50	355·1	1·791	1·051	1·053	1·002
		100	354·8	2·534	1·184	1·183	0·999
	0·980	25	355·2	1·266	1·013	1·015	1·002
		50	355·2	1·791	1·051	1·055	1·004
		100	355·2	2·532	1·183	1·192	1·008

does not affect the main conclusion that in a long cable with enamelled strands the proximity effect is eliminated.

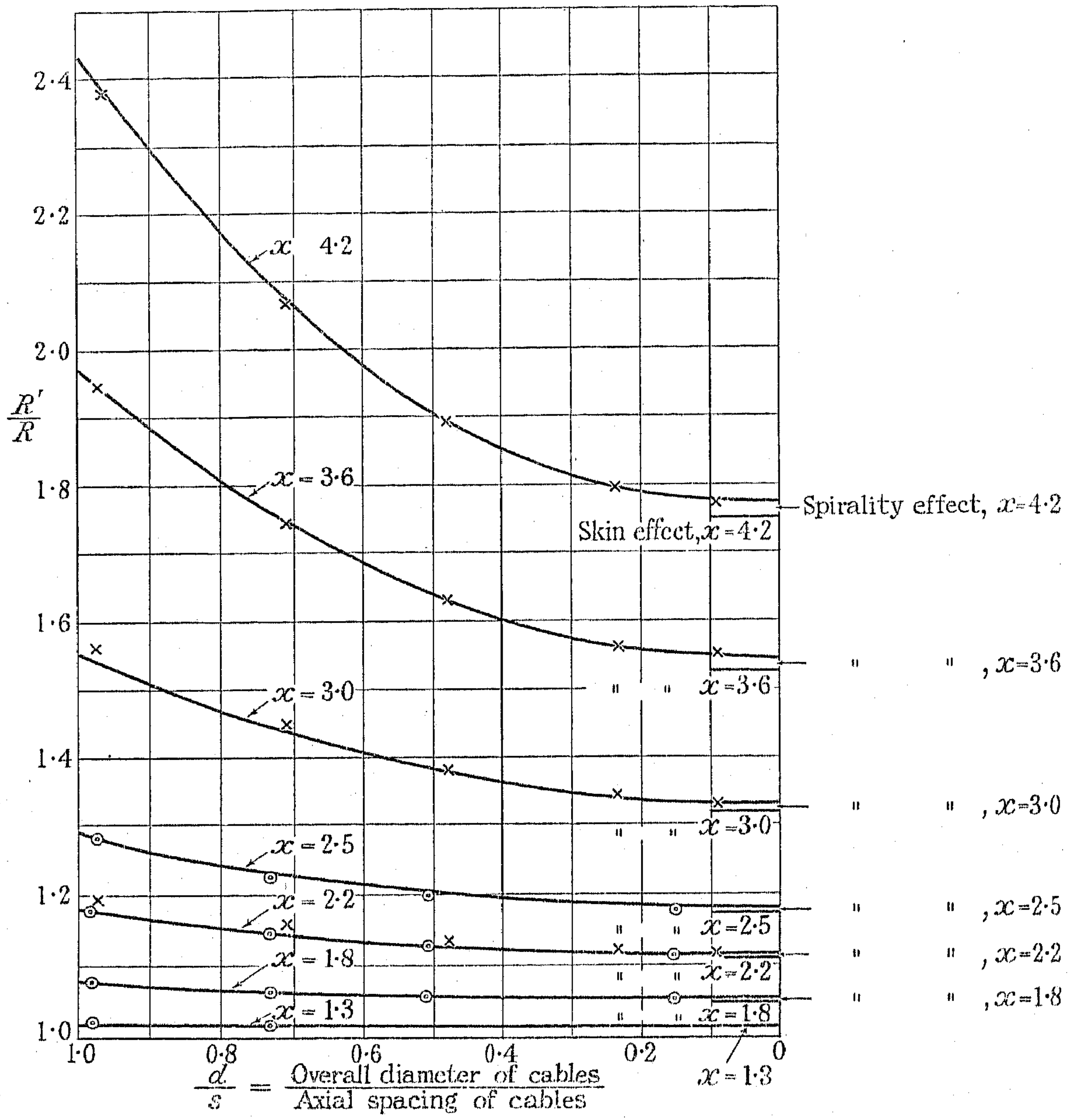

FIG. 3.—Ratio of a.c. resistance to d.c. resistance of lead and return cables with bare strands [curves show the value of R'/R obtained by plotting equation (6)].

Experimental points for 1·87 sq. in. cable shown thus ×
,, ,, ,, 0·68 ,, ,, ,, ,, ⊙
The spirality and skin effects are shown for each value of x at $d/s = 0$.
Proximity effect is shown by the change in the value of R'/R as d/s increases from 0 to 1.

Approximately
$x = 4·2$ corresponds to 1·87 sq. in. cable at 100 cycles.
$x = 3·6$,, ,, ,, ,, ,, ,, 75 ,,
$x = 3·0$,, ,, ,, ,, ,, ,, 50 ,,
$x = 2·2$,, ,, ,, ,, ,, ,, 25 ,,
$x = 2·5$,, ,, 0·68 ,, ,, ,, 100 ,,
$x = 2·2$,, ,, ,, ,, ,, ,, 75 ,,
$x = 1·8$,, ,, ,, ,, ,, ,, 50 ,,
$x = 1·3$,, ,, ,, ,, ,, ,, 25 ,,

In computing the value of R'/R from Equations (1) and (2) it is necessary to know the frequency and the direct-current resistance of the cable per centimetre length. This latter factor was determined by dividing the measured value of the direct-current resistance of the cable by the length between potential points, thus avoiding all assumptions as to resistivity, temperature of the copper, and effective section of the cable. The only precaution necessary was to ensure that the temperature of the cable was the same when carrying alternating current as when carrying direct current. This uniformity of temperature was effectively secured by measuring the direct- and alternating-current resistances of the cable within a minute of each other; and by using only a small current, 100 amperes, so that the self-heating of the cables would be small.

In this connection it should be realized that if R'/R is computed from the dimensions and resistivity of the cable, the resistivity assumed should be that corresponding to the working temperature of the cable.

The results on the cables with bare strands are very interesting. In the first place, it may be found, by plotting the value of R'/R for a given cable at a given frequency (i.e. for a definite value of x) against the ratio of diameter of cable to axial spacing, that the value of R'/R at infinite spacing is a small but definite amount greater than the value obtained for cables with enamelled strands. The increase, which is the spirality effect, by definition, varies up to a maximum of 2 per cent for the largest cable at 100 cycles per second. Its value in the two cables tested was found to be approximately 3 per cent of the total increase of resistance of the cable with alternating current (see Fig. 3), but this value would probably be less in cables with a larger lay ratio, while the contact resistance between strands would influence the value, and this factor might be different in different cables.

For the two cables tested, therefore, the spirality effect $= y_1 = 0\cdot03y$.

As the cables were brought closer together, a marked increase in the value of R'/R was observed, reaching a maximum value of 60 per cent in the case of the largest cable at a frequency of 100 cycles per second. This increase is the proximity effect due to the return conductor, by definition. It was found possible to correlate the values obtained by means of the purely empirical relation given in Equation (5).

Proximity effect due to return conductor

$$= y_2 = 0\cdot94y^{5/4}(d/s)^{2+0\cdot5y^2} \quad . \quad . \quad . \quad (5)$$

where d/s = ratio of overall diameter of cable to axial spacing between lead and return.

This relation is valid only in the range of x between 0 and 4·2 and holds only for the two cables tested. It is probable, however, that further work on other cables would show that the equation could be applied in other cases by a small change of the values of the coefficients. It should be noted that the overall diameter used in the ratio (d/s) in Equation (5) is the maximum diameter of the copper, and not the diameter over insulation.

The value of R'/R for the cables with bare strands is then given by Equation (6) to within 2 per cent.

$$\begin{aligned} R'/R &= 1 + \text{skin effect} + \text{spirality effect} + \text{proximity effect} \\ &= 1 + y + y_1 + y_2 \\ &= 1 + 1\cdot03y + 0\cdot94y^{5/4}(d/s)^{2+0\cdot5y^2} \quad . \quad . \quad (6) \end{aligned}$$

All the measurements were made with a view to obtaining the value of R'/R by measurement and by computation to an accuracy of about one-quarter of 1 per cent. The accuracy of the direct-current potentiometers and the accuracy of the alternating-current bridge were first tested out by measuring known resistances. The errors in these measurements were found to be appreciably less than 0·1 per cent. Measurements were then made on a pair of round rods of copper, in order to compare the value of R'/R obtained by measurement with the computed value.

The length of rod available was 10 ft., only a third of the length of cables tested. In order to approximate to conditions required for an infinitely long conductor, extension leads were fitted to the rod at each end so as to carry the current in the same straight line for a further 10 ft. This precaution was also observed in testing the cables. Initial measurements showed that great accuracy of alignment of these extension leads was not necessary. The measurements on round rod are shown in Table 2, and it may be seen that for values of x up to 3·5 the measured value of R'/R does not depart from the computed value by more than 0·4 per cent. The calibration of the mutual inductance indicated that an error of about 0·2 per cent would be introduced into the alternating-current resistance measurement on account of the residual phase angle of the inductance at 100 cycles per second, and the remaining 0·2 per cent may be divided up among all the other measurements involved. In order to determine if any error was caused by the finite length of conductor, the distance between potential points was progressively diminished from 300 cm to 50 cm (axial spacing between conductors 33 cm) but no marked change in the value of R'/R was observed (see Table 2). It may be assumed, therefore, that the overall errors of the measurements on these cables in no case exceeded 0·4 per cent, and in most cases were appreciably less than this.

TABLE 5.

Particulars of Cables. (Bare Wires.)

Cable pair	Number of strands	Diameter of strands, in.	Effective cross-sectional area, sq. in.	Overall diameter		Length between potential points, cm
				in.	cm	
No. 5	169	0·120	1·87	1·835	4·66	903·1
No. 6	61	0·120	0·68	1·086	2·76	905·5

EXPERIMENTAL RESULTS.

The experimental results are shown in Tables 2 to 6 and in Figs. 2 and 3. In Table 2 are shown the results of the measurements on round rod which were made in order to verify the accuracy of the method. The maximum discrepancy between the theoretical and experimental values of R'/R is 0·4 per cent. In Table 4 and Fig. 2 the results of the measurements on the cables with enamelled strands are shown. It may be seen from the table that, except when the lead and return cables are very close together, the experimental value of R'/R agrees with the value given by Equation (2) to within 1 per cent. The value of R'/R is practically independent of the distance between lead and return conductors. It is probable that the slight increase of R'/R, less than 1 per cent, which occurs when the cables are brought very close together is due to the short length of cable tested, resulting in unequal impedances of the various strands in a given layer. Table 6 and Fig. 3 show the results of the measurements on the cables with uninsulated strands. The computed value of R'/R was obtained by evaluating Equation (6). The terms y_1 and y_2 are purely empirical. The contact resistance between the strands in a given layer is an important factor in determining the magnitude of the proximity effect (y_2). In the two cables tested there was no insulation wrapped over the cables, so that the contact resistance between strands was probably higher than would normally be the case in an insulated cable. It is to be expected, therefore, that the proximity loss in an insulated cable will be somewhat greater than in the cables tested, although the influence of such factors as the lay ratio and the diameter of the strands may modify this conclusion.

TABLE 6.

Tests on Cables with Bare Strands.

Overall diameter / Axial spacing $= d/s$	Frequency $= f$ cycles/second	D.C. resistance between potential points, microhms	x	Skin effect $= y$	Spirality effect $= y_1$	Proximity effect $= y_2$	Computed value of $R'/R = 1 + y + y_1 + y_2$	Measured value of R'/R	Measured R'/R / Computed R'/R
No. 5 Cable Pair (169 *Strands*):									
0·0930	25	126·59	2·117	0·097	0·003	0·000	1·100	1·105	1·005
	50	126·44	2·996	0·317	0·010	0·002	1·329	1·336	1·005
	75	126·30	3·671	0·555	0·017	0·003	1·575	1·580	1·003
	100	126·15	4·242	0·768	0·023	0·003	1·794	1·792	0·999
0·2335	25	127·06	2·113	0·096	0·003	0·003	1·102	1·107	1·005
	50	127·13	2·988	0·314	0·009	0·011	1·334	1·343	1·007
	75	127·17	3·659	0·551	0·017	0·020	1·588	1·590	1·001
	100	127·22	4·224	0·761	0·023	0·024	1·808	1·806	0·999
0·479	25	127·22	2·112	0·096	0·003	0·011	1·110	1·117	1·006
	50	127·20	2·987	0·314	0·009	0·049	1·372	1·379	1·005
	75	127·17	3·659	0·551	0·017	0·092	1·660	1·656	0·998
	100	127·14	4·225	0·762	0·023	0·124	1·909	1·903	0·997
0·710	25	127·31	2·111	0·096	0·003	0·025	1·124	1·137	1·012
	50	127·33	2·985	0·313	0·009	0·109	1·431	1·442	1·006
	75	127·34	3·656	0·550	0·017	0·214	1·781	1·776	0·997
	100	127·42	4·221	0·760	0·023	0·305	2·088	2·079	0·996
0·971	25	127·70	2·108	0·095	0·003	0·047	1·145	1·166	1·018
	50	127·66	2·982	0·312	0·009	0·206	1·527	1·548	1·014
	75	127·64	3·652	0·548	0·016	0·416	1·980	1·982	1·001
	100	127·61	4·217	0·759	0·023	0·622	2·404	2·389	0·994
No. 6 Cable Pair (61 *Strands*):									
0·1533	50	352·2	1·797	0·052	0·002	0·001	1·055	1·055	1·000
	75	352·2	2·201	0·111	0·003	0·001	1·115	1·115	1·000
	100	352·3	2·542	0·186	0·006	0·003	1·195	1·190	0·996
0·509	50	352·3	1·797	0·052	0·002	0·006	1·060	1·061	1·001
	75	352·3	2·201	0·111	0·003	0·016	1·130	1·128	0·998
	100	352·1	2·542	0·186	0·006	0·029	1·221	1·214	0·994
0·726	25	350·6	1·274	0·014	0·000	0·002	1·016	1·018	1·002
	50	350·9	1·801	0·053	0·002	0·013	1·068	1·069	1·001
	75	351·2	2·205	0·112	0·003	0·032	1·147	1·146	0·999
	100	351·3	2·545	0·187	0·006	0·061	1·254	1·242	0·990
0·979	25	354·3	1·267	0·013	0·000	0·004	1·017	1·022	1·005
	50	354·0	1·793	0·052	0·002	0·022	1·076	1·083	1·006
	75	353·5	2·197	0·111	0·003	0·058	1·172	1·177	1·004
	100	352·1	2·542	0·186	0·006	0·110	1·302	1·300	0·998

The value of x, the independent variable, used in computing the value of R'/R in Tables 2, 4, and 6, was deduced from the experimental results by means of the equation below:—

$$x = \sqrt{\{(8\pi f)/(R \times 10^9)\}}$$

$$= 5{\cdot}013\sqrt{\frac{\text{Frequency in cycles per second} \times \text{length between potential points in centimetres}}{\text{Measured direct-current resistance of conductor between potential points, in ohms,} \times 10^9}}$$

(*a*) *Preliminary Tests on Round Copper Rod.*

Diameter of rod = 3·197 cm = d.

Distance between axes of lead and return = 33·9 cm = s

$$d/s = 0{\cdot}0949$$

The skin effect was computed from Table 8 in Appendix IV, and the proximity effect due to the return conductor, which at this spacing was always less than 0·5 per cent, was computed from S. Butterworth's formula (30).

(*b*) *Tests on Cables with Insulated Strands.*

The computed value of R'/R in Table 4 was obtained by evaluating Equation (2), since the spirality and proximity effects were suppressed by the insulation between the strands. The value of y was obtained from Table 8 in Appendix IV. The experimental results, at the largest spacing, are shown graphically in Fig. 2.

(*c*) *Tests on Cables with Bare Strands.*

The computed value of R'/R in Table 6 was obtained by evaluating Equation (6), which with the exception of the skin-effect term, y, is a purely empirical relation, devised for the purpose of correlating the results, and indicating approximately the magnitudes of the skin, spirality, and proximity, effects. The results are shown graphically in Fig. 3. In this figure, curves are drawn showing the variation of R'/R with axial spacing between cables for values of x of 4·2, 3·6, 3·0, 2·5, 2·2, 1·8 and 1·3. These values of x correspond approximately to the values of x for the two cables tested at the four frequencies of 100, 75, 50, and 25 cycles per second. The experimental points shown on the figure are corrected values, allowing for the small differences between the real values of x as given in Table 6 and the values of x assumed for the curves.

CONCLUSIONS.

The results given in Table 4 show that the alternating-current resistance of a cable without lead covering and with insulated strands is the same, at a given frequency, as the alternating-current resistance of a solid round rod of equal direct-current resistance per unit length, the return conductor being concentric or at a considerable distance. In the case of the cable, however, the alternating-current resistance is independent of the distance between lead and return conductors, since the proximity effect is suppressed by the prevention of current flow from strand to strand. The spirality effect, which in any case is very small, is suppressed in this case also.

The results in Table 6 show that the alternating-current resistance of a cable with uninsulated strands is always higher at a given frequency than the alternating-current resistance of a similar cable with insulated strands. The increase of resistance appears to be due partly to the spiralling of the strands and partly to the effect of the return conductor. Both effects are caused by current flowing from strand to strand along paths of unknown resistance. The spirality effect in the two cables tested was found to be approximately 3 per cent of the increase of resistance due to skin effect. In these two cables the lay ratio was approximately 13, which is probably the smallest ratio likely to be encountered in practice. This small ratio would tend to make the spirality effect large. On the other hand, the contact resistance between strands would probably be higher than in an ordinary cable with insulation, and this would tend to reduce the spirality effect. The effect of spiralling is, however, so small, resulting in an increase of R'/R of less than 2 per cent for the 2-sq. in. cable at the highest frequency, 100 cycles per second, that for ordinary commercial practice it can safely be neglected.

On the other hand, the proximity effect due to the return conductor, when the two cables were nearly touching, was found to be of the same order of magnitude as the skin effect and hence could not be neglected in the case of large cables. An empirical law linking up the observed results showed that the proximity effect was inversely proportional to the square of the ratio of the axial distance between conductors to the overall diameter of conductors, for small cables. In the largest size of cable at the highest frequency tested it was found that the proximity effect was more nearly proportional to the power 2·3 of the ratio of the axial distance between conductors to the overall diameter of the conductors. As in the case of spirality effect, the magnitude of the proximity effect would be dependent on both the lay ratio and the contact resistance between the strands, but it is possible that the law of variation of proximity effect with spacing between conductors is independent or nearly independent of these factors.

It may be seen from Tables 4 and 6 that the increase of resistance due to skin effect varies from 1½ per cent of the direct-current resistance in the case of the 0·7-sq. in. cable at 25 cycles per second up to 76 per cent in the case of the 1·9-sq. in. cable at 100 cycles per second.

The maximum proximity effect, that is, when the lead and return conductors are nearly touching, varies from ½ per cent of the direct-current resistance for the 0·7-sq. in. cable at 25 cycles per second up to 62 per cent for the 1·9-sq. in. cable at 100 cycles per second. The spirality effect varies from under 0·1 per cent of the direct-current resistance for the 0·7-sq. in. cable at 25 cycles per second to 2½ per cent for the 1·9-sq. in. cable at 100 cycles per second.

The suppression of the proximity effect by enamelling the strands might provide a valuable saving in cable costs in cables of large cross-section laid close together.

LINES OF FURTHER WORK.

It is considered that further work on this subject could usefully be carried out along four lines.

1. *Proximity Effect in Cables with Uninsulated Strands.*

The results of the tests already carried out show that this effect is by no means negligible, but as the results were obtained on two cables only they are limited in value. A full study of proximity effect would include an investigation of the effect of (i) the lay ratio and (ii) factors influencing the contact resistance between the strands.

The contact resistance between the strands would probably be dependent on the surface condition of the strands and the tightness of the winding. It is probable that when the paper insulation is wound on a cable the contact resistance between strands is reduced below that of the cables of bare strands which were tested and which were not bound in any way. The oil impregnation probably has the same effect.

If, however, cables with enamelled strands were adopted generally, in cases where the proximity effect was likely to be serious, the need for this line of research would no longer exist, since the proximity effect would be suppressed.

2. *Polyphase Circuits and Groups of Cables.*

In the case of polyphase circuits or circuits in which two or more conductors are connected in parallel, the proximity effect would be entirely different from that existing in the case of a single-phase system of lead and return conductor, and would require a separate investigation. Here again, the suppression of the proximity effect, by the adoption of cables with enamelled strands, would render this work unnecessary.

3. *Investigation of the Effect of a Lead Sheath.*

This is probably the most useful line of immediate advance. It would be of advantage to investigate first the effect of the lead sheath on cables with enamelled strands. The investigation would involve a study of single-phase and polyphase circuits and of bonded and unbonded sheaths.

The extension of this research to cables with uninsulated strands would be of little value unless the researches on proximity effect in cables with uninsulated strands were also undertaken.

4. *The Effect of a Rope Core.*

A considerable reduction of the skin effect in large cables may be obtained by filling the centre of the cable with a rope core. At power frequencies, for cables up to 2-sq. in. section, this procedure involves an increase in the overall diameter of the cable for a given alternating-current resistance. The proximity effect would probably be very little altered by the presence of the rope core.

APPENDIX I.

THE MEASUREMENT OF LOW IMPEDANCES OF LOW POWER FACTOR WITH ALTERNATING CURRENT.

The resistances measured in this research on skin effect varied from 0·0001 ohm up to 0·0005 ohm, while the initial measurements on round rod involved the measurement of a resistance very little greater than 0·00001 ohm. In order to avoid heating the copper the small current of 100 amperes was used throughout, with the exception of a few check measurements at 50 and 200 amperes. The power factor (cos ϕ) of the resistances measured varied from 0·06 to 0·8, with a corresponding variation of tan ϕ from 17 to 0·75.

The principle of the bridge used for these measurements may be seen from Fig. 4. T is a perfect current transformer having a ratio k between the primary and secondary currents. A perfect current transformer is defined as being a transformer in which there is no leakage or capacitance current between the windings, and in which the secondary current is a constant multiple or sub-multiple of the primary current and in exact time-phase opposition. The ratio of the current transformer used throughout this research was 1 000. M is a variable mutual inductance and R_1 is a non-inductive four-terminal resistance connected in series with the primary of the inductance to the secondary of the current transformer. A high resistance, r_1, also non-inductive, is connected across the voltage terminals of R_1. This high resistance has a tapping point which may be moved continuously over the whole range of r_1 so that the voltage tapped off may be varied from zero up to the full voltage across r_1. The tapped portion of the resistance is denoted by r_2. The unknown four-terminal resistance is denoted by X. One of its voltage terminals is connected directly to the end of r_1, while the other voltage terminal is connected through the secondary of the mutual inductance M and a vibration galvanometer to the tapping point. If the maximum value of M and the value of R_1 are suitably chosen, it is possible by varying M and the position of the tapping point to reduce the galvanometer deflection to zero. It may be necessary to reverse the connections to the current terminals of R_1 if the polarity is wrong.

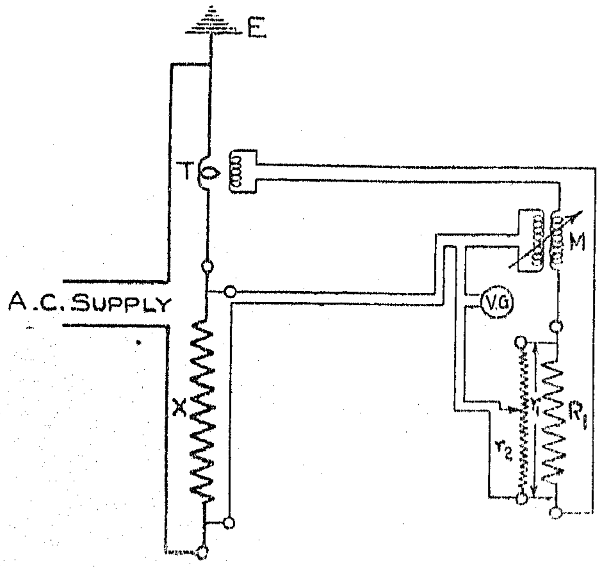

FIG. 4.—A.C. bridge for measuring low resistances.

The equations of balance of the bridge, when the galvanometer deflection is zero, are given below:—

Let the unknown impedance X be denoted by

$$R' + j\omega L'$$

where R' denotes the alternating-current resistance of the impedance, and
$\omega L'$ denotes the alternating-current reactance of the impedance.

Let the current through X be denoted by I.

Then the current through the primary of M and through $R_1 = I/k$. At balance

$$IR_1r_2/[k(r_1 + R_1)] = I(R' + j\omega L') - j\omega MI/k \quad . \quad . \quad (7)$$

Equating the in-phase and quadrature components

$$R' = R_1r_2/[k(r_1 + R_1)] \quad . \quad . \quad . \quad . \quad (8)$$

$$L' = M/k \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The simplicity of these equations of balance is obtained by neglecting the residual inductances of the resistances R_1, r_1, and r_2, by assuming that the secondary e.m.f. of the mutual inductance is in exact quadrature with the primary current, and by assuming the phase angle of the current transformer to be zero. These conditions cannot be absolutely realized in practice, and the maximum permissible errors will now be considered.

Let the secondary current of the transformer

$$= i = I(1 + j\psi)/k$$

Let the secondary e.m.f. of the mutual inductance

$$= \omega Mi(\theta + j)$$
$$= \omega MI(1 + j\psi)(\theta + j)/k$$

Let the impedance of $R_1 = R_1(1 + j\alpha)$
the impedance of $r_1 = r_1(1 + j\beta)$
the impedance of $r_2 = r_2(1 + j\gamma)$

It will be assumed that the residual errors of the transformer, mutual inductance, and the resistances R_1, r_1, and r_2, are so small that their products may be neglected, and that r_1 is large compared with R_1.

Voltage across r_2

$$= ir_2R_1(1+j\gamma)(1+j\alpha)/\{r_1(1+j\beta)+R_1(1+j\alpha)\}$$

$$= IR_1r_2\{1+j(\alpha-\beta+\gamma+\psi)\}/[k(r_1+R_1)] \text{ approx.} \quad (10)$$

Secondary e.m.f. of mutual inductance

$$= (j\omega MI/k) + \omega MI(\theta - \psi)/k \quad . \quad . \quad (11)$$

Therefore, equation of balance is

$$(R' + j\omega L') - (j\omega M/k) - \omega M(\theta - \psi)/k$$
$$= R_1r_2\{1 + j(\alpha - \beta + \gamma + \psi)\}/[k(r_1 + R_1)] \quad (12)$$

Equating in-phase and quadrature components

$$R' = R_1r_2/[k(r_1 + R_1)] + \omega M(\theta - \psi)/k \quad . \quad . \quad (13)$$

$$L' = (M/k) + R_1r_2(\alpha - \beta + \gamma + \psi)/[\omega k(r_1 + R_1)] \quad (14)$$

The error expressed as a fraction of the resistance measured, involved in using Equation (8) instead of Equation (13) to estimate R' is, therefore, equal to

$$\omega M(\theta - \psi)(r_1 + R_1)/(R_1r_2)$$

The tangent of the phase angle of the unknown resistance $= \omega M(r_1 + R_1)/(R_1r_2)$. Therefore

Error $= (\theta - \psi) \times$ tangent of phase angle of resistance measured . . . . (15)

Equation (15) shows that the error involved in the measurement of resistance by this method is equal to the sum or difference (since both θ or ψ may be positive or negative) of the residual phase angles of the mutual inductance and the current transformer, multiplied by the tangent of the phase angle of the resistance measured. The residual phase angles of the resistances R_1, r_1, and r_2, provided they are reasonably small, do not introduce any appreciable error into the resistance measurement.

The largest value of tan θ involved in the series of measurements described in this report was 17, so that the maximum error involved in the measurement of R' was $17(\theta - \psi)$. In order that this error should be less than 0·25 per cent $(\theta - \psi)$ had to be less than 0·00015 radian, or 0·5 minute.

The mutual inductance used in these tests was calibrated and its phase defect found to be approximately 0·4 minute at the highest frequency used. On the other hand, the phase angle of the very best current transformers with nickel-iron cores exceeded a minute when working on the burden involved in this bridge. The current transformer used in these tests was constructed by Messrs. Elliott Brothers (London), Ltd., and was specially designed for working with a secondary burden of 100 volt-amperes at a rated current of one ampere. The secondary winding consisted of 1 997 turns, while an opening 3 in. in diameter was left for the insertion of any desired number of primary turns. At 100 volt-amperes burden this turn compensation of 0·15 per cent was sufficient to bring the ratio very close to 2 000 to 1 or 1 000 to 1 with a primary winding of two turns. At the somewhat smaller and more inductive burden used in these tests, the ratio was somewhat less than 1 000 and the secondary current vector reversed was lagging behind the primary current vector.

With these conditions it was possible by placing resistance and inductance shunts across the secondary terminals of the transformer to send a current through the mutual inductance and R_1 which was accurately in phase opposition to the current through the impedance X, and which was exactly one-thousandth of it in magnitude. The adjustment of the shunts to the correct value was carried out by means of a second bridge, and this adjustment was made to an accuracy of approximately 0·1 minute for phase angle and a few parts in 10 000 for ratio. A change-over switch was used for switching the vibration galvanometer from one bridge to the other.

The complete double bridge is shown in Fig. 5, which also shows the lay-out of the cables and the d.c. connections. R_2 is a four-terminal resistance with a residual phase angle of less than 0·05 minute at 100 cycles per second and a resistance within two parts in 10 000 of 0·01 ohm. R_3 is a four-terminal resistance with a residual phase angle of less than 0·05 minute at 100 cycles per second and a resistance within two parts in 10 000 of 10 ohms. With the change-over switch in position 1, the voltage-drop across R_2 may be balanced against the voltage-drop in R_3 by adjusting the resistance and inductance shunts connected across the terminals of the current transformer. When balance is obtained the current through R_3, R_1, and the primary of the mutual inductance, is within a few parts in 10 000 of one-thousandth of the current through R_2 and the unknown impedance, and is in phase opposition to it to within 0·1 minute. If the change-over switch is now moved to position 2 and the current and frequency are unaltered the unknown impedance may be measured by the main bridge as already described, and Equation (8) may be used to estimate the value of R' with an error of not more than 0·25 per cent, if the power factor of the impedance X is not less than 0·06. The resistance r_1 had an effective value of 100 ohms and was constructed on the Kelvin–Varley slide principle, thus minimizing the errors due to variable contacts, while at the same time enabling a very fine subdivision of the voltage across r_1 to be obtained. The slide was constructed with three dials and a slide wire graduated into 100 divisions, so that one division on the slide wire corresponded to 0·00001 of the whole voltage across r_1.

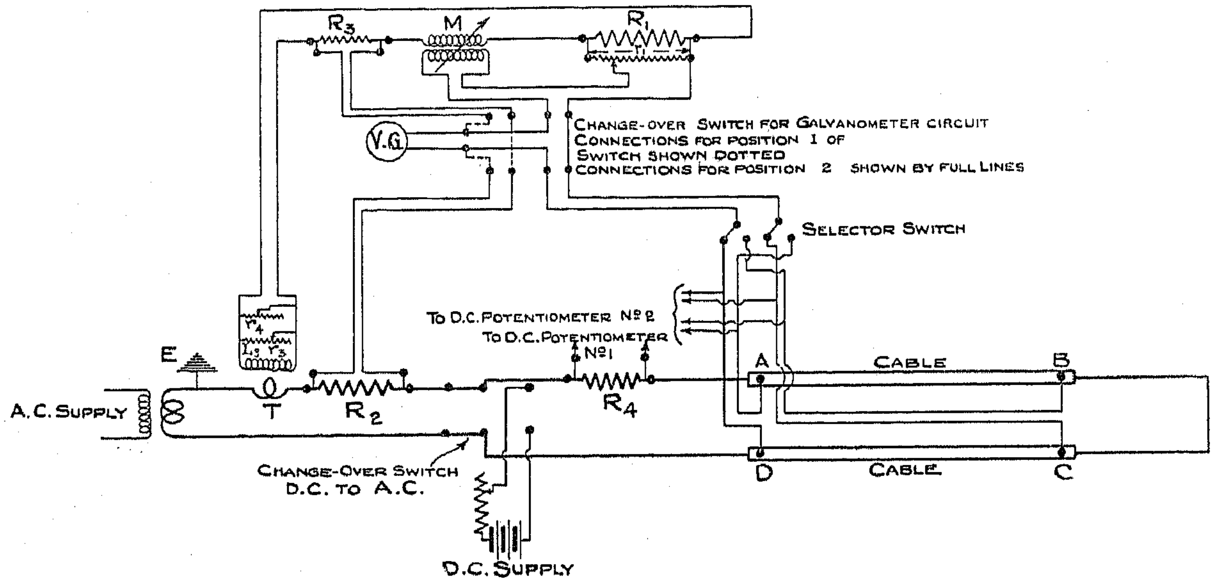
R3
M
R1
r1
V.G
Change-over Switch for Galvanometer circuit
Connections for position 1 of
Switch shown dotted
Connections for position 2 shown by full lines
Selector Switch
To D.C. Potentiometer No 2
To D.C. Potentiometer No 1
r4
L3 r3
E
A.C. Supply
T
R2
R4
A
B
Cable
D
C
Cable
Change-over Switch
D.C. to A.C.
D.C. Supply

FIG. 5.—Diagram of connections for measuring the resistance of cables with direct and alternating current.

NOTE.—All pairs of leads, with the exception of the main cable circuit, were twisted together.

This resistance, r_1, was connected across a four-terminal resistance R_1 of such a value that the voltage-drop across R_1 was greater than the resistance-drop across the impedance to be measured. The values of R_1 used in this series of measurements on cables were 0·2 ohm, 0·4 ohm, and 1·0 ohm, according to the resistance of cable to be measured.

APPLICATION OF THIS BRIDGE TO THE MEASUREMENT OF THE ALTERNATING-CURRENT RESISTANCE OF CABLES.

In using this bridge it is necessary that the leads from the voltage terminals of the unknown impedance should be carefully twinned together so that no e.m.f. should be induced in the galvanometer circuit other than the secondary e.m.f. of the mutual inductance. In measuring the impedance of a straight cable the voltage terminals are necessarily separated by the full length of the cable, and a very considerable e.m.f. may be induced in the galvanometer circuit by the magnetic field due to the current in the cable. Such an e.m.f. would be nearly in quadrature with the resistance-drop in the cable and would, therefore, only introduce a serious error into the inductance measurement. Since, however, where skin effect and proximity effect are appreciable, the total current in the cable is made up of a number of component currents in different time-phase, it is quite possible for a small e.m.f. in phase with the resistance-drop in the cable to be introduced into the galvanometer circuit. This would directly affect the resistance measurement. In order to avoid this error the resistances of both lead and return cables were measured. The voltage leads to the terminals B and C (see Fig. 5) and to the terminals A and D were twin flexible cords. Thus any e.m.f. introduced into the galvanometer circuit was exactly the same for both measurements, while the voltage-drops in the two cables were of opposite phase, so that the error was exactly reversed. The mean of the two measurements gave the mean resistance and the mean inductance of the two cables. That this precaution was desirable was shown by the observations. The direct-current resistances of the two cables were practically the same in all cases, but the differences in the apparent alternating-current resistances of the two cables amounted to as much as 0·5 per cent in some cases, so that the error involved if a single measurement had been taken would have been 0·25 per cent, a small but easily avoidable error.

The only remaining sources of error were the small lengths of lead between B and C and between A and D which could not be twinned and the possibility of mutual inductance between the cable system and the variable mutual inductance. The lengths of lead between B and C and between A and D were perpendicular to the direction of current flow in the cables, so that any e.m.f. induced in them must have been exceedingly small. The mutual inductance was designed to be astatic and was placed several yards away from the cables. It was turned through 180° and an additional reading taken. As no change of apparent resistance was observed, it was deduced that no appreciable inductive action was occurring between it and the cables.

The current supply was obtained from an independent generator. When working at a frequency of 50 cycles per second it was found that the currents in circuits from 10 to 20 yards distant induced slight e.m.f. in the cables, resulting in a periodic variation of the galvanometer deflection, since the frequency of the disturbing current was in general slightly different from the frequency of the cable current. Under these conditions, it was quite impossible to balance the bridge accurately, and most of the measurements were made at night when the other circuits were not carrying current.

APPENDIX II.

A Review of Some of the Approximate Formulæ for Skin Effect in a Straight Solid Conductor of Circular Cross-Section and in a Cable.

The most accurate method of evaluating the skin effect in round rod is by means of a specially constructed table, such as Table 8 in Appendix IV. There are, however, cases where a simple algebraic formula has advantages over tables, even if some accuracy is lost. A number of different approximate formulæ have been put forward by various authors at different times. Most of these formulæ are only valid for a certain range of the independent variable, but the useful ranges of the formulæ have not always been clearly stated, so that it has not always been obvious which formula is the best to use in the particular conditions of any given case.

The independent variable adopted is not always the same. The most usual independent variable is that denoted by x in this report. This variable is equal to the square root of the ratio of 8π multiplied by the frequency in cycles per second to the direct-current resistance of the conductor in C.G.S. units per centimetre length. It is usual to consider the frequency low if x is less than unity and the frequency high if x is greater than 5, but this convention is relative since, for a given frequency, x may be given any value by varying the value of the direct-current resistance per centimetre length. The convention is, however, very convenient and will be adopted in this review.

The independent variable, x, may also be expressed in terms of the dimensions and resistivity of the conductor. This procedure is liable to lead to serious error if the formulæ are applied to cables, since the diameter of a cable is greater than the square root of $(4/\pi) \times$ cross-sectional area of the copper. A further uncertainty is introduced by the reduction of effective cross-sectional area due to the greater length of the spiralled strands as compared with unspiralled strands. This reduction is usually assumed as equal to 2 per cent, but its actual value is often less than this. By adopting the definition of x given in this report all ambiguity is avoided and the formulæ may be used for estimating the skin effect in cables as well as in round rod.

In order to prevent confusion, all the approximate formulæ are given in terms of the independent variable x, although this was not always the form adopted by the originators of the formulæ.

For small values of x the skin effect is proportional to x^4, and for large values of x the skin effect is directly proportional to x. Approximate formulæ fall, therefore, naturally into three groups.

(a) *Low-Frequency Formulæ.*

These formulæ are asymptotic to the true formula at $x = 0$.

(b) *High-Frequency Formulæ.*

These formulæ are asymptotic to the true formula at large values of x, and are therefore straight-line formulæ.

(c) *Formulæ Valid for All Frequencies.*

These formulæ are asymptotic to the true formula at large values of x and approximate to it at smaller values of x.

All the formulæ given are tabulated, for ease of reference, at the end of this Appendix.

(a) *Low-Frequency Formulæ.*

Formula No. 1:

$$y = x^4/192 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

Formula No. 2:

$$y = \frac{x^4}{192}\left(1 - \frac{x^4}{240}\right) \quad . \; . \; . \; . \; . \; . \; . \quad (17)$$

Formula No. 3:

$$y = \frac{x^4}{192}\left\{1 - \frac{x^4}{240}\left(1 - 11\frac{x^4}{896}\right)\right\} \quad . \; . \quad (18)$$

Formula No. 4:

$$y = \frac{1}{2}\left\{\left(1 + \frac{x^4}{48}\right)^{\frac{1}{2}} - 1\right\} \quad . \; . \; . \; . \quad (19)$$

If the true formula for skin effect is written in the form of an infinite series, the approximate formulæ 1, 2, and 3, may be obtained by taking respectively one, two, and three terms. Formula No. 1 is correct within 1 per cent of $(1 + y)$[*] for the range of x from 0 to $2 \cdot 2$. Formulæ Nos. 2 and 3 have a slightly greater range of applicability, but the increased range is not worth the additional complication, and for values of x above 3 these formulæ depart further from the true formula than formula No. 1. Formula No. 4 is an empirical formula which is correct to within 1 per cent of $(1 + y)$ for the range of x from 0 to $3 \cdot 3$. The curves given in Fig. 6 show how these approximate formulæ depart from the true formula at the larger values of x.

(b) *High-Frequency Formulæ.*

Formula No. 5:

$$y = x/(2\sqrt{2}) - 1 \quad . \; . \; . \; . \; . \; . \; . \quad (20)$$

Formula No. 6:

$$y = x/(2\sqrt{2}) - 0 \cdot 74 \quad . \; . \; . \; . \; . \; . \quad (21)$$

At very high frequencies formula No. 5 is a good approximation, but it is hopelessly in error for all moderate values of x. Formula No. 6 is a much better approximation and is correct to within 1 per cent of

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[*] If spirality and proximity effects are small, $(1 + y) = R'/R$ approx.

$(1 + y)$ for all values of x greater than $2 \cdot 7$. It is more often given as

$$y = \frac{x}{2\sqrt{2}} - \frac{3}{4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

but this change of the constant increases the maximum error of the formula to about $1\frac{1}{4}$ per cent of $(1 + y)$ at $x = 5$, and limits the range of validity for $1\frac{1}{4}$ per cent accuracy to the values of x above $2 \cdot 8$.

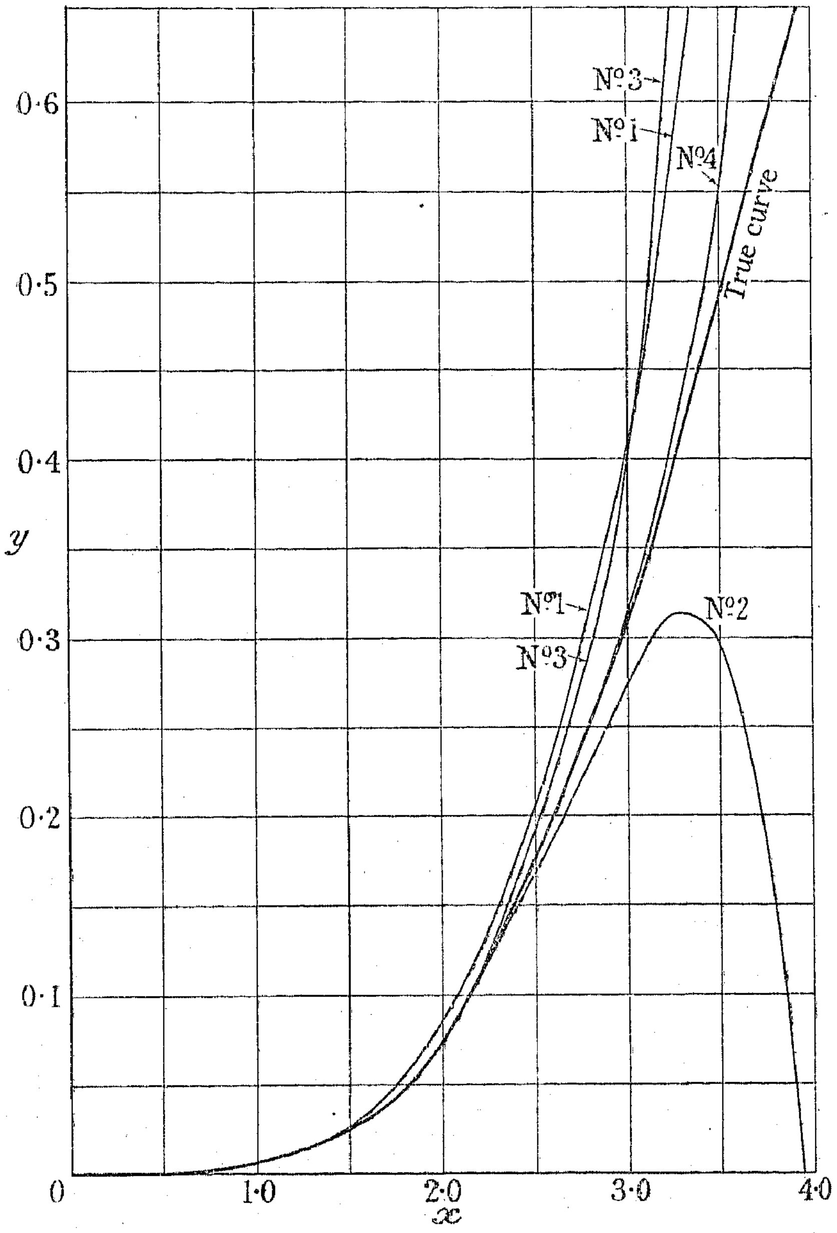

FIG. 6.—Approximate formulæ for skin effect (the true curve for skin effect is shown by the heavy line).

Formula (1). $y = x^4/192$.

" (2). $y = \frac{x}{192}\left(1 - \frac{x^4}{240}\right)$

" (3). $y = \frac{x^4}{192}\left[1 - \frac{x^4}{240}\left(1 - 11\frac{x^4}{896}\right)\right]$

" (4). $y = \frac{1}{2}\left[\sqrt{\left(1 + \frac{x^4}{48}\right)} - 1\right]$.

Formulæ Nos. 5 and 6 are compared with the true formula by means of curves in Fig. 7.

(c) *Formulæ Valid for All Frequencies.*

Formula No. 7:

$$y = \frac{1}{4}\left\{(729 + 8x^6)^{\frac{1}{6}} - 3\right\} \quad . \quad . \quad . \quad . \quad (23)$$

Formula No. 8:

$$y = \frac{x^2}{2(\sqrt{2x} - 1)} - 1 \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Formula No. 7 is an empirical formula developed by A. Levasseur (77) in which the maximum error for any value of x is less than $1\frac{1}{4}$ per cent of $(1 + y)$. Formula No. 8 is known as the "Penetration Formula," although, as far as the investigator is aware, it has not previously been given in this form. Its maximum error is $5\frac{1}{2}$ per cent of $(1 + y)$ at $x = 2 \cdot 8$, and in the form given by Equation (24) it should not be used below $x = \sqrt{2}$, for which value $y =$ zero by this formula, the true value being $0 \cdot 020$. For accurate work, this formula is not recommended, but it has a wide range of application for rough work and certain peculiar advantages of its own. The formula, which was originally intended for high-frequency work, was developed from Formula No. 5, which is valid only at very high frequencies. Although the penetration formula has often been used for low-frequency work, it must be regarded as a fortunate chance that the error involved is so small, since the phenomena assumed do not correspond at all closely

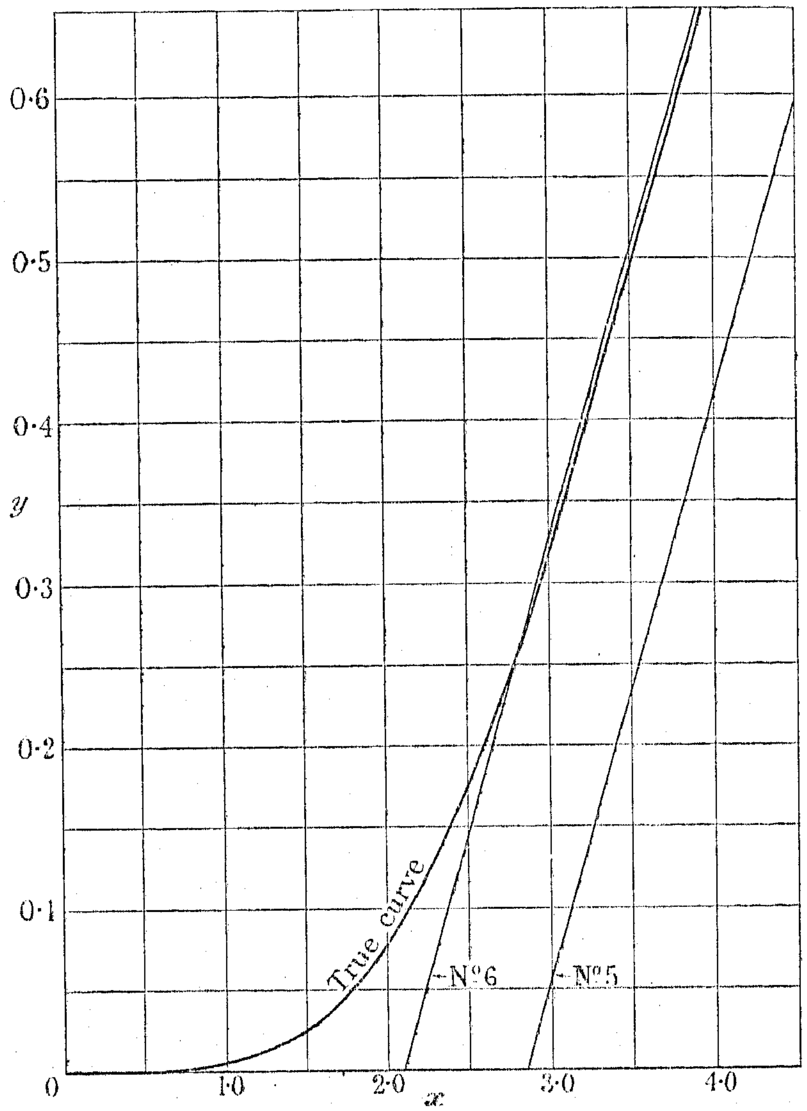

FIG. 7.—Approximate formulæ for skin effect (the true curve for skin effect is shown by the heavy line).

Formula (5). $y = \frac{x}{2\sqrt{2}} - 1$.

" (6). $y = \frac{x}{2\sqrt{2}} - 0 \cdot 74$.

to the phenomena actually taking place, at low or at high frequencies. The formula, as given by Equation (24), is applicable to solid rods or to cables, but the penetration depth, defined below, and the theoretical development of the formula are only applicable to solid rods, since the diameter of the rod is introduced.

At very high frequencies the current density falls off extremely rapidly from the surface to the centre of the conductor, and for all practical purposes the current may be assumed to be concentrated in a small stratum of the conductor near the surface, the remainder of the conductor being idle. If the thickness of this stratum be "t" it may be said that the current penetrates to a depth "t." The penetration formula assumes that the current is uniformly distributed over a thin stratum of the conductor near the surface and is zero elsewhere.* The resistance of this thin stratum per unit length is approximately

$$1/(\pi t d g) \text{ ohms}$$

where d = diameter of conductor for solid rod in centimetres;
t = depth of penetration in centimetres;
g = conductivity in mhos per centimetre cube.

The resistance of the whole conductor to direct current is

$$4/(\pi d^2 g) \text{ ohms}$$

so that $R'/R = d/(4t)$

neglecting proximity effects, and

$$y = \frac{d}{4t} - 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Now $x = \sqrt{8\pi f/(R \times 10^9)} = \pi d\sqrt{(2fg/10^9)}$

so that we have, by equating the right-hand sides of Equations (20) and (25),

$$\frac{1}{2}\pi d\sqrt{(fg/10^9)} = d/(4t)$$

Therefore $$t = \frac{1}{2\pi\sqrt{fg/10^9}} = \frac{d}{\sqrt{2x}} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

so that the depth of penetration is dependent only on the frequency and the conductivity of the material, and not at all on the diameter of the conductor. The advantages of this formula are so obvious, since for a given frequency and a given material the depth of penetration is constant, that it has been widely used for low frequencies as well as high, although not originally intended for this purpose. It has also been used in calculations for tubes, it being assumed that if the current penetrates to a certain depth only, then the best thickness of tube is the penetration depth, since this gives R'/R equal to unity for minimum external diameter. The errors involved in these assumptions may easily exceed 10 per cent at low frequencies, but, nevertheless, this method of calculating tube dimensions has a rough-and-ready value and has been widely used. At a frequency of 50 cycles per second, for copper of conductivity $5 \cdot 8 \times 10^5$ mhos per centimetre cube, the penetration depth is $0 \cdot 936$ centimetre.

If the penetration depth given by Equation (26) is used at low frequencies, it may be a large fraction of the whole radius of the conductor and hence

$$R' = 1/[\pi t g(d - t)] \text{ ohms;}$$

the approximation given before, namely $R' = 1/(\pi t g d)$ being no longer sufficiently accurate.

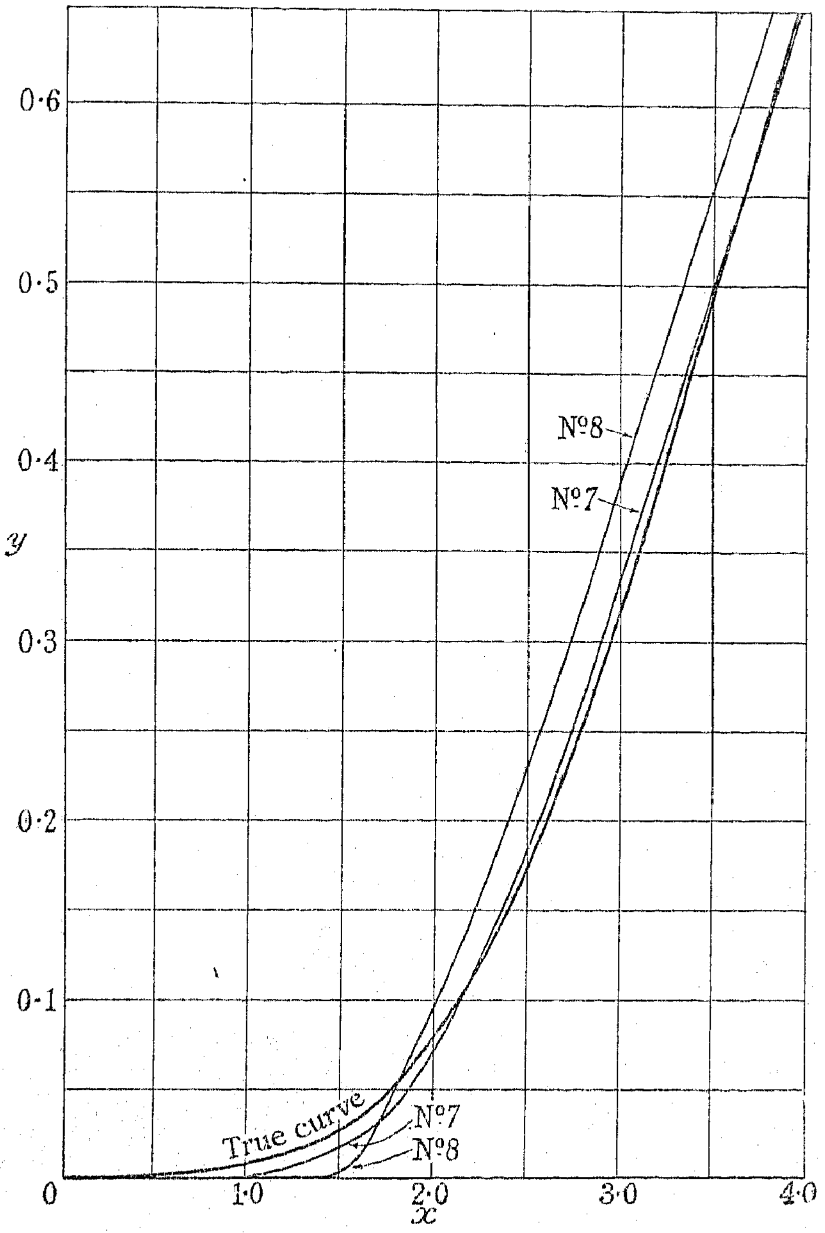

FIG. 8.—Approximate formulæ for skin effect (the true curve for skin effect is shown by the heavy line).

Formula (7). $y = \frac{1}{4}\left[\left(729 + 8x^6\right)^{\frac{1}{6}} - 3\right].$

" (8). $y = \frac{x^2}{2(\sqrt{2x} - 1)} - 1.$

Therefore $$R'/R = d^2/[4t(d - t)] \quad . \quad . \quad . \quad . \quad (27)$$

Substituting the value of t given by Equation (26),

$$R'/R = \pi d^2 fg/\left\{2\pi d\sqrt{(fg/10^9)} - 1\right\} = x^2/[2(\sqrt{2x} - 1)] \ (28)$$

From Equation (26) it may be seen that when $x = \sqrt{2}$ the penetration depth is equal to the radius of the conductor. In other words, for all values of x less than $\sqrt{2}$, the penetration formula assumes that R'/R = unity,

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* This assumption of uniform distribution is not true, and therefore the actual effective depth of penetration is greater than that assumed by the "Penetration Formula."

TABLE 7.

Formulæ for Skin Effect in a Straight Solid Conductor of Circular Cross-Section and in a Cable.

Independent Variable = $x = \sqrt{8\pi f/(R \times 10^9)}$

Rigid Formula $y = \frac{1}{2}x\left\{\text{ber}\, x\, \text{bei}'\, x - \text{bei}\, x\, \text{ber}'\, x\right\}/\left\{(\text{ber}'\, x)^2 + (\text{bei}'\, x)^2\right\} - 1$

NOTE.—$R'/R = 1 + y$, if spirality and proximity effects are zero.

No.	Approximate formula for skin effect (y)	Range of x for $1\frac{1}{2}$ % accuracy of $(1 + y)$	Remarks	Bibliography reference
1	$\frac{x^4}{192}$	0–2·3	Above $x = 2\cdot3$ error increases very rapidly and formula becomes useless. Formula overestimates skin effect for all values of x	3, 4, & 5
2	$\frac{x^4}{192}\left(1 - \frac{x^4}{240}\right)$	0–2·7	Above $x = 2\cdot7$ error increases very rapidly and formula becomes useless. Formula underestimates skin effect for all values of x	3, 4, & 5
3	$\frac{x^4}{192}\left\{1 - \frac{x^4}{240}\left(1 - 11\frac{x^4}{896}\right)\right\}$	0–2·6	Above $x = 2\cdot6$ error increases very rapidly, the formula overestimating the skin effect	3, 4, & 5
4	$\frac{1}{2}\left\{\left(1 + \frac{x^4}{48}\right)^{\frac{1}{2}} - 1\right\}$ . .	0–3·4	Above $x = 3\cdot4$ error increases rapidly, the formula overestimating the skin effect	13
5	$\frac{x}{2\sqrt{2}} - 1$	60–∞	Below $x = 60$ error increases at a gradually increasing rate, the formula underestimating the skin effect	5
6	$\frac{x}{2\sqrt{2}} - 0\cdot74$	2·65–∞	Below $x = 2\cdot65$ error increases rapidly, the formula underestimating the skin effect	—
7	$\frac{1}{4}\left\{(729 + 8x^6)^{\frac{1}{6}} - 3\right\}$ . .	0–∞	The maximum error of this formula is 1·2 per cent of $(1 + y)$	77
8	$\frac{x^2}{2(\sqrt{2x} - 1)} - 1$	1·7–2·0 4·6–∞	If $(1 + y)$ be taken equal to unity for all values of x less than $\sqrt{2}$, the maximum error of this formula is $5\frac{1}{2}$ per cent of $(1 + y)$ for any value of x. This formula is usually known as the Penetration Formula. Penetration Depth = $1/\left[2\pi\sqrt{(fg/10^9)}\right]$	—

since the penetration is complete. If Equation (24) is evaluated for values of x less than $\sqrt{2}$, absurd values are obtained. In utilizing the "penetration depth" to estimate the alternating-current resistance of a cable, the diameter of an equivalent solid rod should be taken and not the actual diameter of the cable, or serious errors will result. Formulæ Nos. (7) and (8) are compared with the true formula by means of the curves shown in Fig. 8.

The only approximate formula which is valid over the whole range of x from 0 to ∞ and which is reasonably accurate is Formula No. 7. Formula No. 4 may be used for the range of x from 0 to 3, and Formula No. 6 for the range of x from 3 to ∞, and these two formulæ are simpler to evaluate than Formula No. 7. The disadvantage of having to work with two formulæ of limited range will, however, often outweigh the advantage of their simplicity.

In Table 7 all the formulæ are tabulated with references to the original works.

APPENDIX III.

BIBLIOGRAPHY ON COPPER LOSSES IN SOLID AND STRANDED CONDUCTORS OF CIRCULAR CROSS-SECTION, EXCLUDING CONDUCTORS OF MAGNETIC MATERIAL BUT INCLUDING PAPERS ON THE SUBJECT OF SHEATH AND ARMOURING LOSSES IN POWER CABLES.

At the end of the paper by Kennelly, Laws, and Pierce (14), is given a very good Bibliography (1) of over a hundred papers on the subject of skin effect up to the year 1915.

At the end of the paper by Simons (39) is given a Bibliography (2) of nearly 300 papers on the subject of transmission by underground cables.

The present Bibliography only includes works prior to 1925 which are specifically referred to in this paper, or which are not given in the two Bibliographies already mentioned.

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APPENDIX IV.

Tables for the Rapid Calculation of the Skin Effect in a Solid Conductor of Circular Cross-Section and in a Cable.

The computation of skin effect from the infinite series of the ber and bei functions is a laborious process and a number of authors have prepared tables in order to reduce the work involved. The best of these tables was published by E. B. Rosa and F. W. Grover (12, Table 22). In this table the value of R'/R, as given by Equations (1) and (2), is tabulated to an accuracy of one part in 100 000 for values of x in steps of 0·1 from 0 to 5 and in larger steps from $x = 5$ to $x = 100$. First and second differences are given to aid in interpolation. This accuracy is far greater than is normally required, and the interpolation of first and second differences makes the table a little troublesome for rapid work. Table 8 in this paper has therefore been prepared from Table 22 in Rosa and Grover's paper. In this table the value of the skin effect, y, as given by Equation (1), is given to one part in 10 000 for values of x in steps of 0·01 from 0 up to 5. Proportional parts are given for the next decimal place of x, so that it is possible, at a glance, to read off the value of y to one part in 10 000 for any value of x up to 5.

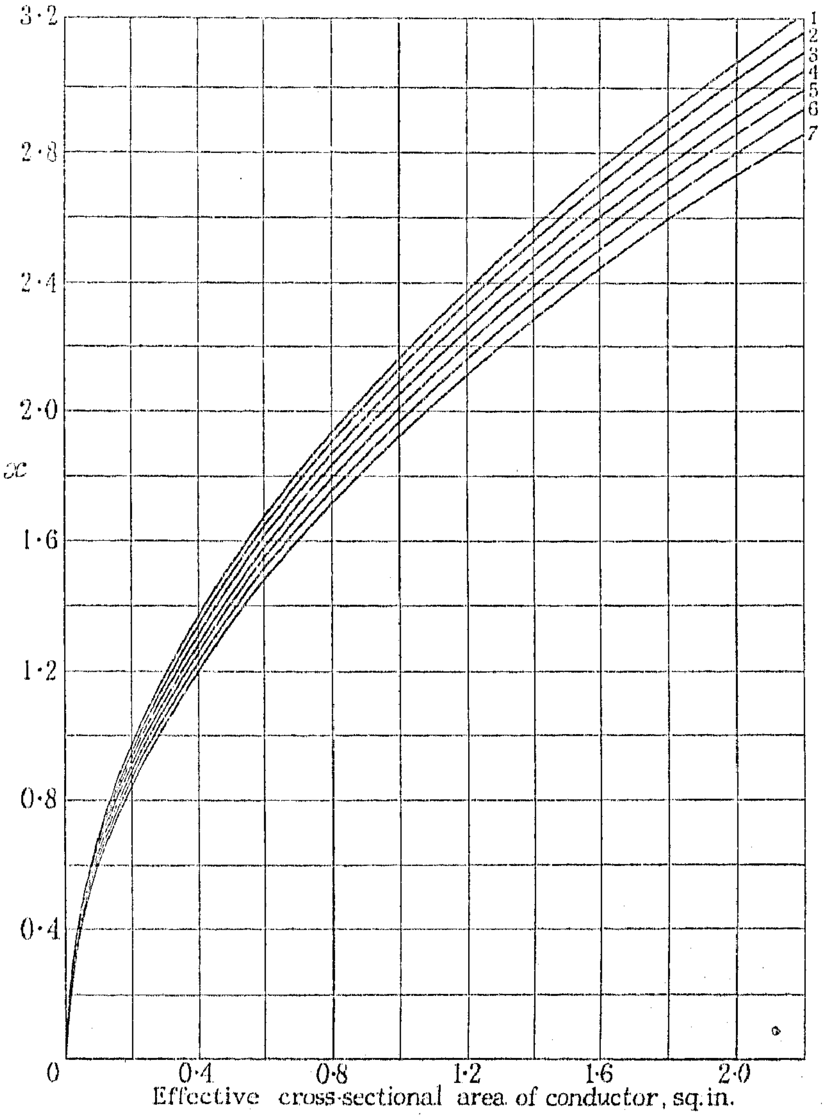

Fig. 9.—Values at x at a frequency of 50 cycles per sec.

Curve 1 for conductor of conductivity 5·8 × 10^5 mhos for a cm cube 100% copper at 20° C.
Curve 2 for conductor of conductivity 5·6 × 10^5 mhos for a cm cube 100% copper at 29° C.
Curve 3 for conductor of conductivity 5·4 × 10^5 mhos for a cm cube 100% copper at 39° C.
Curve 4 for conductor of conductivity 5·2 × 10^5 mhos for a cm cube 100% copper at 50° C.
Curve 5 for conductor of conductivity 5·0 × 10^5 mhos for a cm cube 100% copper at 61° C.
Curve 6 for conductor of conductivity 4·8 × 10^5 mhos for a cm cube 100% copper at 73° C.
Curve 7 for conductor of conductivity 4·6 × 10^5 mhos for a cm cube 100% copper at 87° C.

TABLE 8.

Skin Effect in a Solid Conductor of Circular Cross-Section and in a Cable.

x	Skin effect = y (as given by Equation (1))										Proportional parts								
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
0	0·0000																		
0·1	0·0000																		
0·2	0·0000																		
0·3	0·0000	0·0000	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001									
0·4	0·0001	0·0001	0·0002	0·0002	0·0002	0·0002	0·0002	0·0003	0·0003	0·0003									
0·5	0·0003	0·0004	0·0004	0·0004	0·0005	0·0005	0·0005	0·0006	0·0006	0·0006									
0·6	0·0007	0·0007	0·0008	0·0008	0·0009	0·0010	0·0010	0·0011	0·0011	0·0012	0	0	0	0	0	0	0	0	1
0·7	0·0012	0·0013	0·0014	0·0015	0·0016	0·0017	0·0018	0·0019	0·0019	0·0020	0	0	0	0	0	1	1	1	1
0·8	0·0021	0·0022	0·0024	0·0025	0·0026	0·0028	0·0029	0·0030	0·0031	0·0033	0	0	0	1	1	1	1	1	1
0·9	0·0034	0·0036	0·0038	0·0039	0·0041	0·0043	0·0045	0·0047	0·0048	0·0050	0	0	1	1	1	1	1	1	2
1·0	0·0052	0·0054	0·0056	0·0058	0·0061	0·0063	0·0065	0·0068	0·0070	0·0073	0	0	1	1	1	1	2	2	2
1·1	0·0076	0·0079	0·0081	0·0084	0·0087	0·0090	0·0094	0·0097	0·0100	0·0103	0	1	1	1	2	2	2	2	3
1·2	0·0107	0·0111	0·0114	0·0118	0·0122	0·0126	0·0130	0·0134	0·0138	0·0142	0	1	1	2	2	2	3	3	4
1·3	0·0147	0·0152	0·0156	0·0161	0·0166	0·0171	0·0176	0·0181	0·0186	0·0192	1	1	2	2	3	3	4	4	5
1·4	0·0197	0·0202	0·0208	0·0214	0·0220	0·0226	0·0232	0·0239	0·0245	0·0252	1	1	2	2	3	4	4	5	6
1·5	0·0258	0·0265	0·0272	0·0279	0·0286	0·0293	0·0301	0·0308	0·0316	0·0324	1	1	2	3	4	4	5	6	7
1·6	0·0332	0·0340	0·0349	0·0357	0·0366	0·0375	0·0383	0·0392	0·0402	0·0411	1	2	3	4	4	5	6	7	8
1·7	0·0421	0·0430	0·0440	0·0450	0·0460	0·0470	0·0481	0·0491	0·0502	0·0513	1	2	3	4	5	6	7	8	9
1·8	0·0524	0·0535	0·0547	0·0558	0·0570	0·0582	0·0594	0·0606	0·0619	0·0631	1	2	4	5	6	7	8	10	11
1·9	0·0644	0·0657	0·0670	0·0683	0·0697	0·0711	0·0724	0·0738	0·0753	0·0767	1	3	4	6	7	8	10	11	12
2·0	0·0782	0·0796	0·0811	0·0826	0·0842	0·0857	0·0873	0·0889	0·0905	0·0921	2	3	5	6	8	9	11	12	14
2·1	0·0938	0·0954	0·0971	0·0988	0·1005	0·1022	0·1040	0·1058	0·1076	0·1094	2	4	5	7	9	11	12	14	16
2·2	0·1113	0·1131	0·1150	0·1169	0·1188	0·1207	0·1227	0·1247	0·1267	0·1287	2	4	6	8	10	12	14	16	17
2·3	0·1307	0·1327	0·1348	0·1368	0·1390	0·1411	0·1433	0·1454	0·1476	0·1498	2	4	6	9	11	13	15	17	19
2·4	0·1521	0·1543	0·1566	0·1589	0·1612	0·1635	0·1658	0·1682	0·1716	0·1730	2	5	7	9	12	14	16	19	21
2·5	0·1754	0·1778	0·1803	0·1827	0·1852	0·1878	0·1903	0·1928	0·1954	0·1980	3	5	8	10	13	15	18	20	23
2·6	0·2006	0·2032	0·2058	0·2085	0·2112	0·2138	0·2165	0·2193	0·2220	0·2248	3	5	8	11	13	16	19	22	24
2·7	0·2275	0·2303	0·2331	0·2360	0·2388	0·2417	0·2445	0·2474	0·2503	0·2533	3	6	9	11	14	17	20	23	26
2·8	0·2562	0·2592	0·2621	0·2651	0·2681	0·2711	0·2742	0·2772	0·2803	0·2834	3	6	9	12	15	18	21	24	27
2·9	0·2865	0·2896	0·2927	0·2958	0·2990	0·3021	0·3053	0·3085	0·3117	0·3149	3	6	10	13	16	19	22	25	29
3·0	0·3181	0·3213	0·3245	0·3278	0·3311	0·3344	0·3377	0·3410	0·3443	0·3477	3	7	10	13	16	20	23	26	30

TABLE 8—*continued.*

Skin Effect in a Solid Conductor of Circular Cross-Section and in a Cable.

x	Skin effect = y (as given by Equation (1))										Proportional parts								
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
3·1	0·3510	0·3544	0·3578	0·3611	0·3645	0·3679	0·3713	0·3747	0·3782	0·3816	3	7	10	14	17	20	24	27	31
3·2	0·3850	0·3885	0·3920	0·3955	0·3989	0·4024	0·4059	0·4094	0·4129	0·4165	3	7	10	14	17	21	24	28	31
3·3	0·4200	0·4235	0·4271	0·4306	0·4342	0·4378	0·4414	0·4449	0·4485	0·4521	4	7	11	14	18	21	25	29	32
3·4	0·4557	0·4593	0·4629	0·4666	0·4702	0·4738	0·4774	0·4811	0·4847	0·4884	4	7	11	15	18	22	25	29	33
3·5	0·4920	0·4957	0·4994	0·5030	0·5067	0·5104	0·5140	0·5177	0·5214	0·5251	4	7	11	15	18	22	26	29	33
3·6	0·5288	0·5325	0·5362	0·5399	0·5436	0·5473	0·5510	0·5548	0·5585	0·5622	4	7	11	15	19	22	26	30	33
3·7	0·5659	0·5696	0·5733	0·5771	0·5808	0·5845	0·5882	0·5920	0·5957	0·5994	4	7	11	15	19	22	26	30	34
3·8	0·6031	0·6069	0·6106	0·6144	0·6181	0·6218	0·6256	0·6293	0·6330	0·6368	4	7	11	15	19	22	26	30	34
3·9	0·6405	0·6442	0·6480	0·6517	0·6555	0·6592	0·6629	0·6667	0·6704	0·6741	4	7	11	15	19	22	26	30	34
4·0	0·6779	0·6816	0·6853	0·6891	0·6928	0·6965	0·7003	0·7040	0·7077	0·7114	4	7	11	15	19	22	26	30	33
4·1	0·7152	0·7189	0·7226	0·7263	0·7300	0·7338	0·7375	0·7412	0·7449	0·7486	4	7	11	15	19	22	26	30	33
4·2	0·7523	0·7560	0·7597	0·7634	0·7671	0·7708	0·7745	0·7782	0·7819	0·7856	4	7	11	15	19	22	26	30	33
4·3	0·7893	0·7930	0·7967	0·8004	0·8041	0·8078	0·8114	0·8151	0·8188	0·8225	4	7	11	15	18	22	26	29	33
4·4	0·8261	0·8298	0·8335	0·8361	0·8408	0·8445	0·8481	0·8518	0·8555	0·8591	4	7	11	15	18	22	26	29	33
4·5	0·8628	0·8664	0·8701	0·8737	0·8773	0·8810	0·8846	0·8882	0·8919	0·8955	4	7	11	15	18	22	25	29	33
4·6	0·8991	0·9028	0·9064	0·9100	0·9137	0·9173	0·9209	0·9245	0·9281	0·9317	4	7	11	14	18	22	25	29	33
4·7	0·9353	0·9389	0·9425	0·9461	0·9497	0·9533	0·9569	0·9605	0·9641	0·9677	4	7	11	14	18	22	25	29	32
4·8	0·9713	0·9749	0·9785	0·9821	0·9857	0·9892	0·9928	0·9964	1·0000	1·0035	4	7	11	14	18	21	25	29	32
4·9	1·0071	1·0107	1·0142	1·0178	1·0214	1·0249	1·0285	1·0321	1·0356	1·0392	4	7	11	14	18	21	25	29	32
5·0	1·0427																		
6·0	1·3936																		
7·0	1·7432																		
8·0	2·0945																		
9·0	2·4464																		
10·0	2·7986																		

The evaluation of x, the independent variable, may be made very quickly if the frequency and the direct-current resistance per centimetre are known.

For rough work, at the standard frequency of 50 cycles per second, the value of x is given in Table 9 for cross-sectional areas of copper up to 2 square inches and for three different temperatures of copper. The actual conductivity assumed is given at the head of each column for reference purposes. In cases where the temperature of the copper and the cross-sectional area of the conductor are known more accurately, the value of x may be obtained with greater precision from the curves given in Fig. 9.

TABLE 9.

Values of x at a Frequency of 50 Cycles per Second. Conductivity of Conductor (mhos per Centimetre Cube) = g.

Effective cross-sectional area of conductor in square inches = A'	$x = 0{\cdot}002847\sqrt{(gA')}$		
	$g = 5{\cdot}800 \times 10^5$ copper at 20° C.	$g = 5{\cdot}188 \times 10^5$ copper at 50° C.	$g = 4{\cdot}693 \times 10^5$ copper at 80° C.
0·1	0·686	0·649	0·617
0·2	0·970	0·917	0·873
0·3	1·187	1·123	1·069
0·4	1·371	1·297	1·234
0·5	1·533	1·450	1·380
0·6	1·679	1·589	1·511
0·7	1·814	1·716	1·632
0·8	1·939	1·835	1·745
0·9	2·057	1·946	1·851
1·0	2·168	2·051	1·951
1·1	2·274	2·151	2·046
1·2	2·375	2·247	2·137
1·3	2·472	2·339	2·224
1·4	2·565	2·427	2·308
1·5	2·655	2·512	2·390
1·6	2·742	2·594	2·468
1·7	2·827	2·674	2·544
1·8	2·909	2·752	2·618
1·9	2·988	2·827	2·689
2·0	3·066	2·901	2·759

No table is given in this report for evaluating proximity effect in cables since the formula put forward, Equation (5), is of uncertain value. Further experimental work is needed before this or some other formula can be established as being reliable.

Table 8 gives the values of y to one part in 10 000 for values of x in steps of 0·01 from 0 to 5, with proportional parts for steps of 0·001. The independent variable is given by

$$x = \sqrt{8\pi f/(R \times 10^9)}$$

$$= \sqrt{\frac{8\pi \times \text{Frequency in cycles/second}}{\text{Direct-curren tresistance per cm length of conductor, in ohms,} \times 10^9}}$$

Above $x = 5$

$$y = \frac{x}{2\sqrt{2}} - 0{\cdot}74$$

with an error not exceeding 0·7 per cent. Above $x = 10$, this formula is correct to within 0·1 per cent.

Table 9 gives the values of x in terms of the effective cross-sectional area of conductor in square inches and the conductivity of the copper, at the standard frequency of 50 cycles per second, for cross-sectional areas up to 2 square inches and for three conductivities of copper, corresponding approximately to the temperatures of 20° C., 50° C., and 80° C. The curves in Fig. 9 may be used in place of Table 9 for more precise work.

Effective cross-sectional area of conductor = $1/(gR)$

= 1/(Conductivity × direct-current resistance per centimetre length)

For solid conductors the effective cross-sectional area is equal to the actual cross-sectional area. For cables the effective cross-sectional area is less than the cross-sectional area of the copper on account of the increase of linear resistance due to spiralling. It is also considerably less than $\pi/4$ multiplied by the square of the overall diameter, on account of the air spaces between the strands.

$x = 0{\cdot}002847\sqrt{(gA')}$ at 50 cycles per second,

where g = conductivity of copper in mhos per cm cube, and

A' = effective cross-sectional area of conductor in square inches.

SOME NOTES ON RATES OF RISE OF RESTRIKING VOLTAGE SUBSEQUENT TO INTERRUPTION OF ALTERNATING-CURRENT POWER CIRCUITS.*

By C. H. FLURSCHEIM, B.A., Associate Member.

(*Paper first received 7th June, and in final form 17th September,* 1934.)

SUMMARY.

The observed effect of restriking-voltage rates of rise on the performance of various types of circuit breaker is given, and high rates are shown to increase greatly the severity of the interrupting duty independently of kVA, and consequently to be a factor of considerable importance in the choice of circuit breakers. An indication is made as to where severe conditions are likely to occur on a system.

The causes of the high-frequency oscillations consequent to interrupting fault power are analysed, the rate of rise of restriking voltage is defined, and the effect on this rate of different factors which cannot normally be controlled, such as asymmetry and arc characteristics, are discussed.

The physical constants and factors inherent to the type of system and fault affecting these oscillations, and formulæ for the rate of rise for simple circuits, are given. A method of solution for multi-frequency circuits, based on lumped constants, is described, and in the Appendix the principles for solving long lines employing distributed constants are outlined.

(1) INTRODUCTION.

For several years it was realized that some factor other than voltage and current must be affecting the operation of circuit breakers when interrupting fault currents. Under similar conditions of kVA and system voltage, duplicate breakers gave a wide variation in performance when installed in different circuits, even though they were relatively consistent when tested repeatedly on the same plant. It was not until 1927 that these inconsistencies were attributed to high-frequency voltage oscillations, termed "restriking voltage," following on the final current-zero before arc extinction. The frequency of these oscillations is determined by the capacitance and self-inductance of the external circuit to which a breaker is coupled, and varies with the system design.

That such phenomena existed had been known for several years previously. The theory that these surges might affect circuit-breaker operation was advanced by Hilliard,† Slepian,‡ Kopeliowitsch,§ Biermanns,|| and Kesselring;¶ and in 1930 Park and Skeats** presented their fundamental paper on restriking rates, giving mathematical analyses of the effects of different types of faults and apparatus.

It is now generally recognized that circuits having relatively high natural frequencies, due to low self-inductance and/or capacitance, and consequently high average rates of rise of restriking voltage, measured as the slope of the first half-cycle of the voltage oscillation, are more difficult to interrupt than similar systems with low frequencies. This has been proved in practice by many engineers, although the degree of the effect has been shown to vary with different principles of circuit-breaker design and construction.

A brief summary of published data is given in Section (2). Some observers have unfortunately published curves representing conclusions without giving individual experimental points and test conditions, vitiating to some degree the value of their work.

There is, however, ample reliable evidence to show that these phenomena are an important factor. It is therefore of value to be able to calculate the rates of rise to be expected in localities where switching troubles are experienced (see Section 3) and also where new circuit breakers are to be installed, since a comparison is then available between service conditions and those under which manufacturers' tests have been made.

This paper aims at presenting the methods of calculation in a manner suitable for general use. Errors of the order of 25 per cent may be expected, since it is usually impossible to obtain the circuit constants with any great accuracy; but as a variation in rates of rise of perhaps 80 to 1 is met in practice, such an error is of little consequence. It should be pointed out that the rates obtained by calculation are those which would result from the use of a theoretically perfect circuit breaker, which interrupts the circuit exactly at a true system-frequency, sine-wave current zero, without distortion of the wave and without leakage flow of current across the arc space subsequent to the zero point. In practice the rates of rise obtained, as measured by a cathode-ray oscillograph, may vary from the theoretical, and the causes of this are discussed in Section (4). This section of the paper is, however, partly speculative, as various arc-resistance characteristics, approximating possible cases, had to be assumed before the effects could be calculated.

Section (5) deals with the theoretical rates of rise for simple circuits. In Section (6), more complicated systems are treated where the mathematics becomes less direct, and in the Appendix a method of solution is given for long lines using "distributed" constants.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† See Reference (1). ‡ *Ibid.*, (2). § *Ibid.*, (3).
|| *Ibid.*, (4). ¶ *Ibid.*, (5). ** *Ibid.*, (6).

(2) OBSERVED EFFECTS OF RESTRIKING VOLTAGE ON CIRCUIT BREAKERS.

J. D. Hilliard* in 1927 pointed out that in tests carried out at St. Paul, Minnesota, on oil circuit-breakers in situations where violent restriking-voltage kicks appeared on the magnetic oscillograph, greatly increased arc durations resulted, the variation being 3 to 1, with a change in rate of rise of about 6 to 1. The latter figure can only be regarded as approximate, owing to the relatively low natural frequency of magnetic oscillograph suspension systems (of the order of 2 000 cycles per sec.).

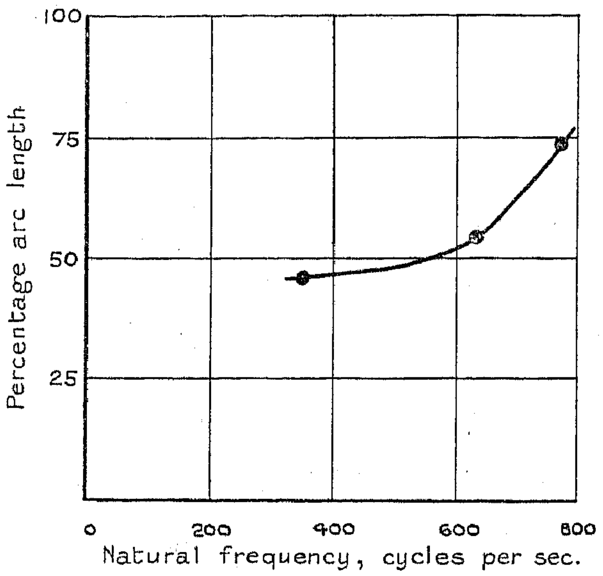


FIG. 1.

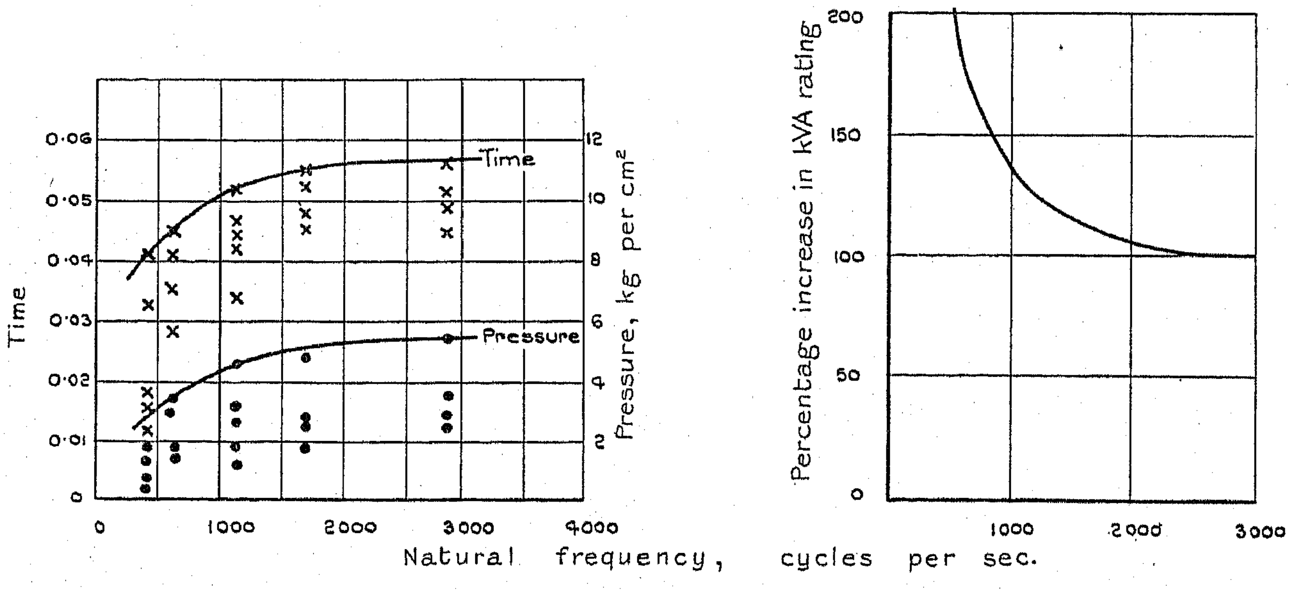
J. Kopeliowitsch† in 1928 published data showing the effect of frequency on arc length in an oil breaker. The three points on the graph in Fig. 1 each represent the longest arc length obtained out of a series of 10 short-circuits under presumably similar conditions. Raising the restriking rate in the ratio of 2·2 : 1 increased the arc length by 1·45 : 1. More recently‡ the same investigator has given curves for an oil breaker showing (*a*) increase in arc duration and tank pressure, and (*b*) decrease in kVA capacity, with increase in natural frequency over a range of 10 to 1 (Fig. 2) assuming the limiting factor to be tank pressure.

In 1929 J. Biermanns* gave curves for an oil breaker over a range of frequency from 500 to 100 000 cycles per sec. (Fig. 3). An increase from 500 to 1 300 cycles per sec. doubled the arc duration, but further increase in frequency resulted in no appreciable change.

TABLE.

Field-Test Comparison of Explosion-Chamber Circuit Breakers.

No. of lines connected to busbar	Calculated volts per microsecond	No. of tests	Average arc duration, cycles	Average arc length, inches
Plain Butt Contacts				
3	270	17	6·2	15·5
1	600	4	7·1	17·0
0	2 400	7	15·0	24·5
Average of 28 tests ..			8·6	18
Oil-Blast Contacts (Butt Type)				
3	270	15	2·6	4·5
1	600	9	3·7	7·1
0	2 400	16	4·1	8·8
Average of 40 tests ..			3·5	6·8



(*a*) (*b*)

FIG. 2.—Effect of change of natural frequency on oil circuit-breaker.

R. M. Spurk and H. E. Strang† in 1931 gave an analysis of the now well-known tests on the 140-kV Philo system, from which the curves shown in Figs. 4(A) and 4(B) have been compiled. These give the envelope of the greatest arc lengths for three different system connections having relative natural frequencies of 1, 2·2, and 8·9, corresponding to recovery rates of 270, 600, and 2 400 volts per microsecond. These figures obtained by calculation agreed closely with checks made by cathode-ray oscillographs. The variation in natural frequency was brought about solely by manipulation of the length of connected transmission lines on the power side of the fault. The tests were made on (*a*) the plain explosion-pot design and (*b*) the oil-blast hollow-tube design fitted with an intermediate floating contact. The Table on page 324 refers to the same set of tests, and clearly shows the effect of the higher rates of rise of restriking voltage.

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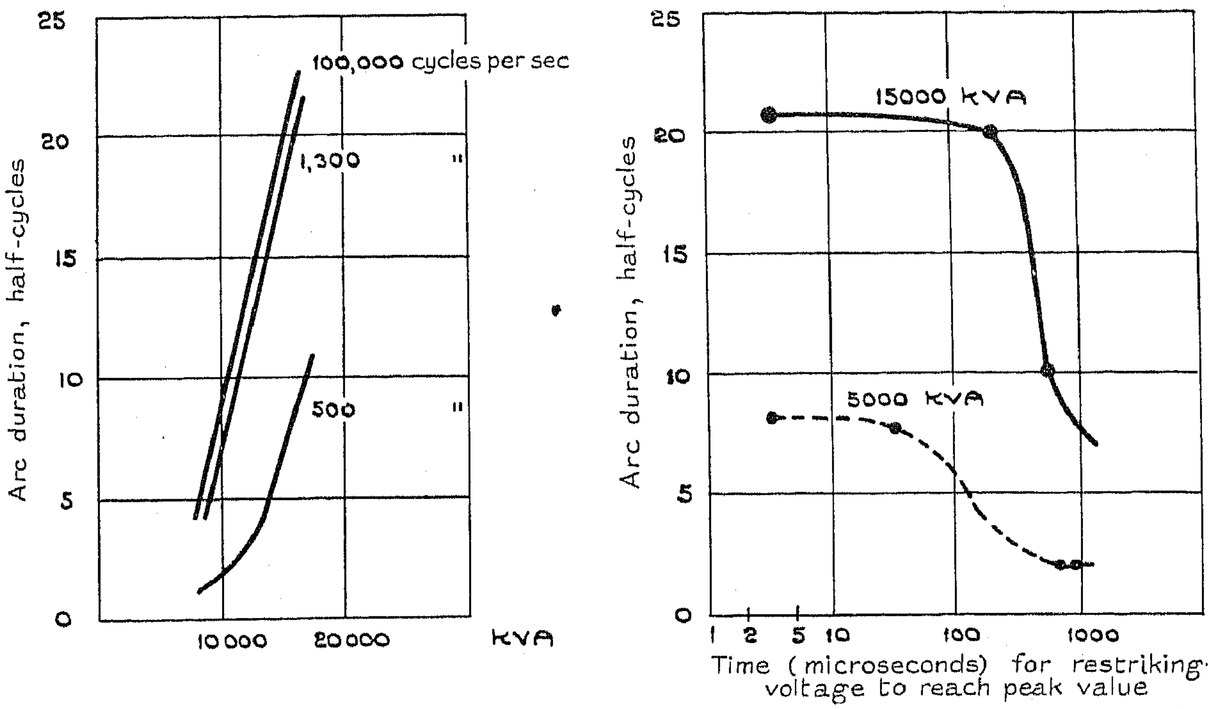
* See References (1) and (6). † *Ibid.*, (3). ‡ *Ibid.*, (8).

* See Reference (4). † *Ibid.*, (9).



(*a*)

(*b*)

FIG. 3.—Influence of natural frequency on an oil circuit-breaker.

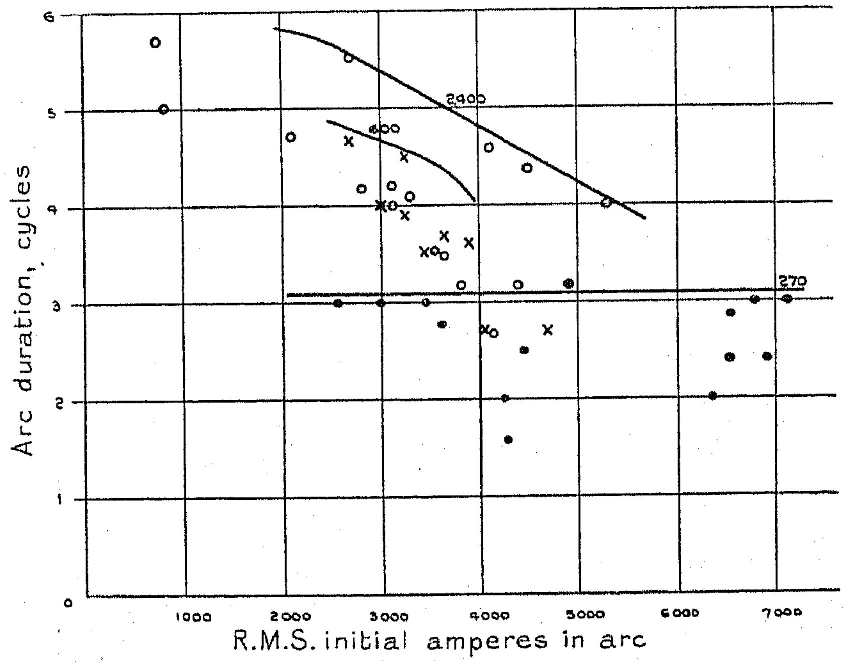


FIG. 4(A).—Effect of restriking rate on oil-blast contacts (140 kV).

● 270 volts per microsecond connection.
× 600 volts per microsecond connection.
○ 2 400 volts per microsecond connection.

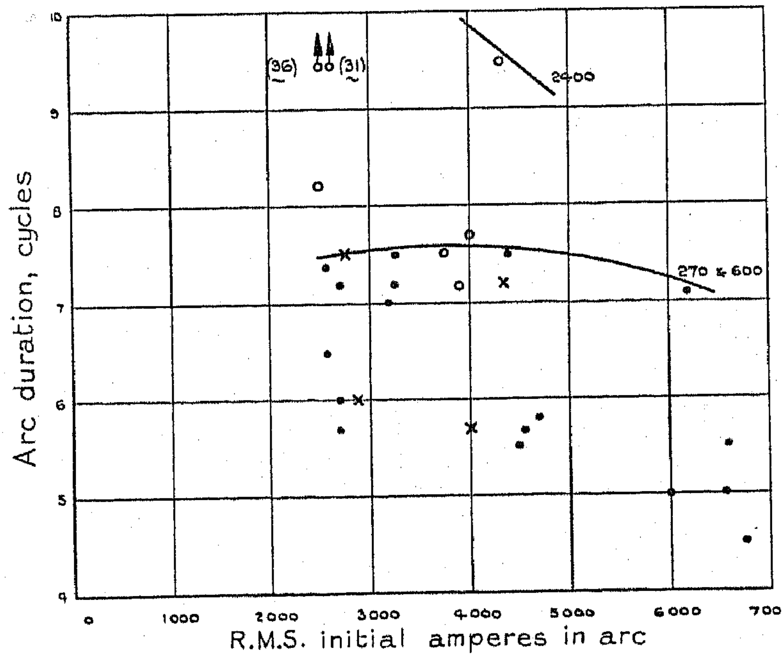


FIG. 4(B).—Effect of restriking rate on butt-type explosion contacts (140 kV).

● 270 volts per microsecond connection.
× 600 volts per microsecond connection.
○ 2 400 volts per microsecond connection.

In 1933, tests were carried out on the 15-kV system of the Philadelphia Electric Co. at the Richmond power station, on a 5 000-amp. oil circuit-breaker fitted with cross-jet contacts.* This breaker cleared satisfactorily rates of rise up to 5 000 volts per microsecond on a test circuit arranged to simulate the conditions which may arise with future extensions. In this instance the arc durations were unaffected by restriking rate; the pressures generated in the contact body by the primary arc produced oil velocities great enough for even this unusually high rate of rise. The theoretical restriking rates, which had been calculated previously, checked reasonably with those obtained by cathode-ray oscillographs.

J. Slepian† has advanced the theory that the increase in electric strength caused by deionization between contacts of a breaker must be more rapid than the increase in voltage stress across the contacts, as determined by the rate of rise of restriking voltage, if the arc is to be extinguished.

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* See Bibliography, (13).

† *Ibid.*, (2).

In 1931 D. C. Prince and W. F. Skeats* advanced the new theory that, in controlled oil or gas-blast breakers, interruption is brought about by the positive displacement of the conducting path at a current zero, and its replacement by fresh un-ionized dielectric, rather than by deionization of a relatively stationary path. This theory suggested that since the dielectric will build up at a rate proportional to the oil velocity, this velocity must in turn be at least proportional to the restriking rate for successful operation. This theory does not require any extraordinary synchronization between gas or oil blast and the current zero. It is almost impossible to extinguish an a.c. arc except very close to the current-zero region. The blast will flow past the arc until a zero is reached, and may then be regarded as commencing to displace the conducting path bodily away from the contacts: synchronization is then automatic. With a radial flow (Fig. 6), the dielectric will be built up at one end of the arc only, with a cross blast at both ends. Consequently, the latter arrangement should only require half the blast velocity for a given restriking rate.

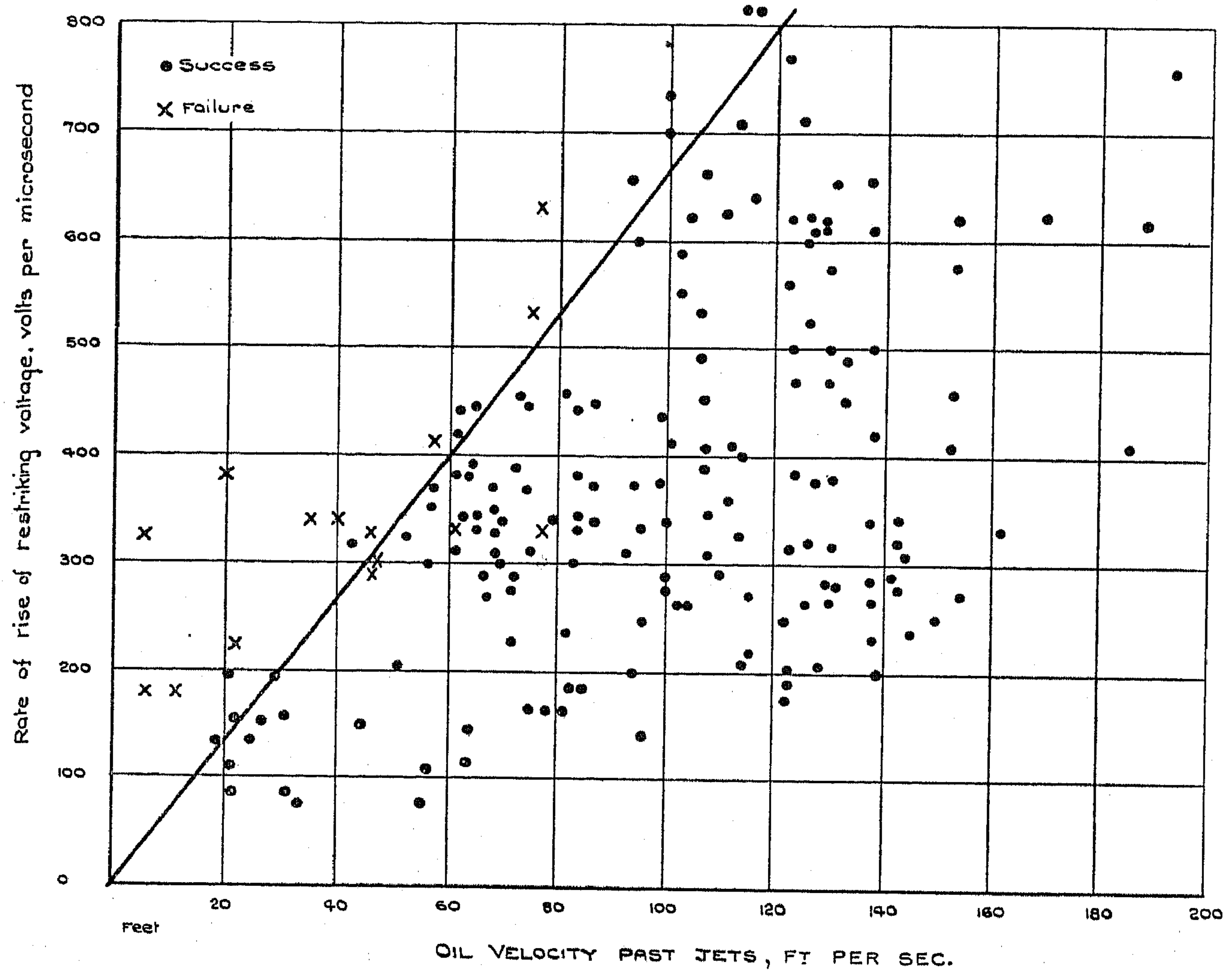

FIG. 5.—Relation between rate of rise of restriking voltage and oil velocity required for interruption, for single-break radial-flow contact.

Quantitative experimental proof of this theory was given by D. C. Prince and E. J. Poitras.* Oil was forced by a spring-pressed piston across the arc space in a radial direction. The oil velocity at any instant was determined by the piston velocity and the relative areas of the piston and the throat through which the oil was forced. Tests were carried out over a range of 80 to 800 volts per microsecond and oil velocities of 6 to 190 ft. per sec. The curves showed that a linear relation existed between oil velocity required for successful operation and restriking rate, independent of line voltage and short-circuit current, within the physical limits of the breaker. One of these curves is reproduced in Fig. 5. Later work is summarized in Fig. 6.† It was shown that within experimental limits of error the cross-blast type was twice as efficient as the radial type, and that eight such cross-blast contacts, arranged in series with reasonable voltage distribution, would interrupt eight times the restriking voltage. Very convincing evidence was thus provided that all controlled-arc breakers depend to a large extent for their success or failure on the relative values of the dielectric velocity produced and the restriking rate to be met.

J. Biermanns‡ gives curves for gas-blast switches analogous to those given for oil breakers (Fig. 7). A marked increase in arc durations is again evident with increase in restriking rate.

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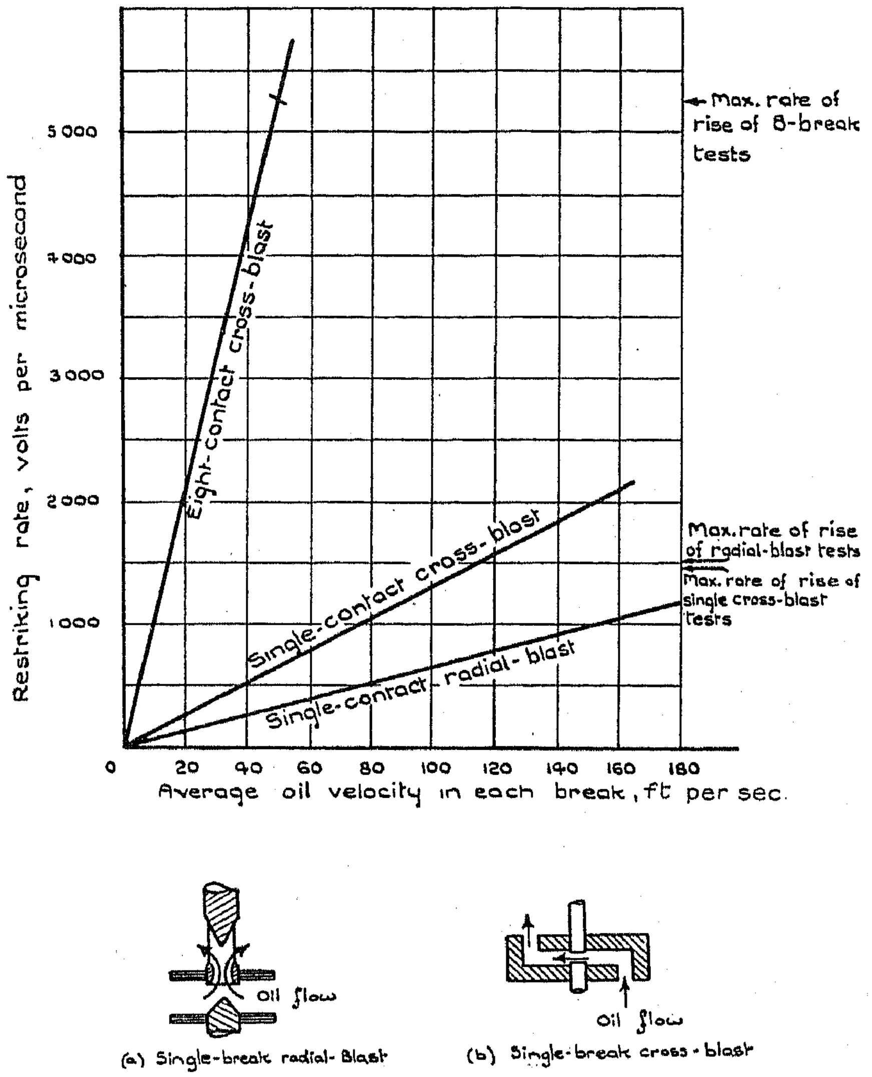
* See Reference (10).

* See Reference (11).

† *Ibid.*, (12).

‡ *Ibid.*, (8).



(a) Single-break radial-Blast (b) Single-break cross-blast

FIG. 6.—Effect of restriking rate on various contact arrangements with mechanically propelled oil blast.

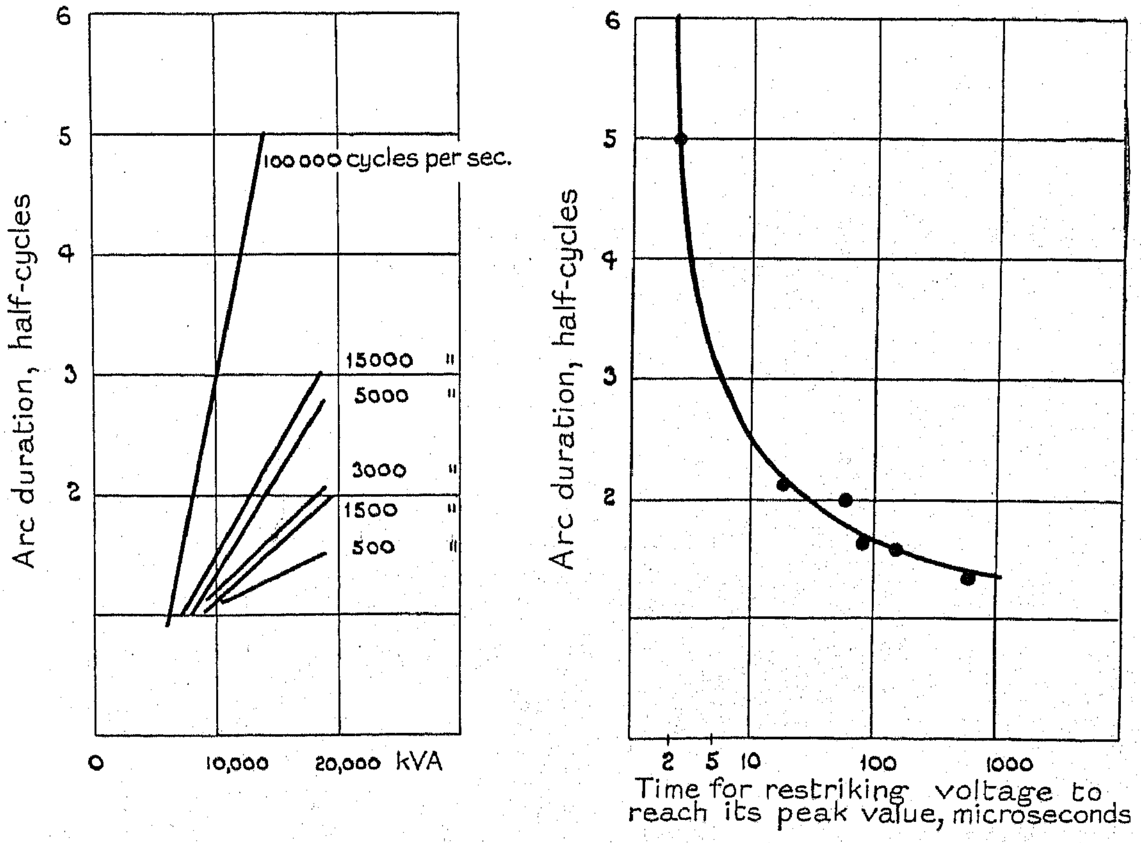


FIG. 7.—Influence of natural frequency on a gas-blast circuit-breaker.

(3) SITUATIONS WHERE HIGH RATES OF RISE OF RESTRIKING VOLTAGE MAY BE EXPECTED.

The conditions for obtaining relatively high rates of rise at the generating voltage are met when the maximum generating or synchronous plant is connected, and when a fault occurs adjacent to the breaker, eliminating the modifying effect of additional cables or transmission lines between the breaker and fault. Severe rates will occur with faults near breakers in base-load stations, where cubicle-type switchgear with short air-insulated connectors to generators is employed, and especially with moulded stone or masonry structure where the effective earth is remote from the busbars.

The inclusion of a reactor in the oscillating circuit will still further increase the rate, and in combination with the above factors will produce the highest possible rate obtained in practice. The use of reactors at substations will also give high frequencies for faults near the reactor, and high rates of rise of restriking voltage, if the reactor represents an appreciable percentage of the system impedance to that point; especially so if high fault kVA is possible.

On e.h.t. systems high rates will occur with breakers adjacent to transformers and with the fault close to the line side of the breaker. The rate of rise of restriking voltage at the power-station end will again be more severe than that at the feeder end, when similar transformers are used. The worst case will be that when the minimum length of transmission line is connected to the system on the breaker side of the fault.

Factors tending to reduce rates of rise are the presence between generator and fault of lead-covered cables, metalclad switchgear, condenser-type busbars and bushings, and the connection of parallel feeders not short-circuited by the fault.

Insufficient calculations have been made to enable definite figures to be given for the rates to be expected under various conditions, but it seems probable that British 11-kV systems could give rates up to 4 000 volts per microsecond, whereas the larger American 15-kV systems may give double this figure. At 132 kV the highest figure will be in the neighbourhood of 3 000 volts per microsecond. These values represent the extreme cases; the values for the normal difficult situations will be considerably lower. The rate for the majority of substation and small power-station breakers will probably not exceed a few hundred volts per microsecond.

High-power short-circuit testing stations employing reactors between generator and breaker, at generating voltage afford higher rates than are normal in service. The extreme cases can be simulated by special test arrangements in which the reactor is placed in the test cell with the breaker,* eliminating the capacitance of the usual connecting leads. At voltages above the generating voltage, testing stations may be either more or less severe than service conditions, depending on the relative natural frequencies of test and service transformers. Since the variation between different designs may be large, no general inference can be drawn.

(4) CAUSES OF RESTRIKING VOLTAGE WAVES.

Consider a sine-wave e.m.f., $e = V \sin \omega t$, impressed on a circuit comprising a reactance, capacitance, and circuit breaker, as shown in Fig. 8. While the contacts are closed, the condenser is short-circuited and the current through the breaker is determined by the reactance. The power factor will then be zero lagging, and at zero current the impressed e.m.f. (e) is a maximum, given by

$$e = V = L \times \text{(Rate of change of current)}$$

Hence the rate of change of current is also a maximum, and if the contacts are suddenly opened at a current-zero no current is broken but this rate instantly becomes zero. We therefore have an e.m.f. given by $e = V \sin \omega t$ suddenly applied at its maximum value to a reactance and capacitance in series; the condenser will charge up to double voltage and discharge back to the supply in the usual oscillatory manner with frequency $f = 1/[2\pi\sqrt{(LC)}]$.

The slope of the first half-cycle of this wave is the measure of the rate of rise of restriking voltage. It may be computed as the slope of the steepest portion of the curve; or as the maximum average slope as given by a tangent to the first oscillation drawn through the point of zero current on the zero-voltage axis; or as the slope from the same point to the peak of the first oscillation. In this paper the second method is employed. It is intermediate in numerical value between the other two, and it has also the physical significance that if the increase in electric strength of the arc path always exceeds this rate, final interruption of the arc is assured.

The rate of rise of restriking voltage for a perfect breaker depends, therefore, on two factors: (i) the natural oscillating frequency, (ii) the value of the impressed e.m.f. at the moment of contact separation. In practice, the rate of rise as measured by cathode-ray oscillographs may vary from the calculated rate on account of any of the following factors: (*a*) D.C. component in current wave. (*b*) Damping of the oscillations owing to circuit resistance. (*c*) Arc voltage. (*d*) Premature cut-off of the current wave before a natural zero of the a.c. wave is reached. (*e*) Leakage current persisting after a current zero.

As regards (*a*), corrections can be made for individual short-circuits for the d.c. component present. The worst case is naturally the most important, and occurs when the wave is symmetrical, so that the possibility of displacement is of little interest. Some allowance can be made in calculation for resistance damping (*b*), which will reduce slightly the severity of the surge. Dealing with (*c*) and (*d*), the effect of arc behaviour and premature cut-off may be to increase or decrease the severity of the short-circuit, but is normally only of small importance, and in any event cannot be said to reduce the relative difficulty of high- and low-frequency systems. They are discussed in more detail below. The only factor which can reduce high- and low-frequency systems to the same level is (*e*), namely leakage current.* The resultant damping may entirely kill the restriking oscillations, but no justification exists for maintaining that this modification makes interruption easier. On the contrary, leakage results in very uncertain operation, and although quantitative evidence as to how the extent of leakage current is affected by system frequency is not available, the fact that arc lengths are considerably longer with high than with low rates of rise on breakers permitting leakage—plain-break oil units, for instance—is well established, indicating that higher frequencies tend to increase leakage. The practical elimination of leakage is a *sine qua non* in modern arc-control devices.

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* See Reference (7).

* See References (14) and (16).

The real criterion of difficulty of interruption for a circuit, therefore, still appears to be the theoretical rate of rise, while the main interest in cathode-ray films is their indication of the manner in which actual breakers perform under conditions of varying severity. The frequency of the circuits can, of course, also be obtained from them, provided leakage has not been excessive; and this, or the use of oscillating-frequency sets, is often the only possible method available of deducing the natural rate of rise.

Effect of Arc Characteristics.

The contacts of a commercial breaker cannot be timed to part at an exact zero, and hence an arc will be drawn between them. Since the arc has a variable resistance, its effect on the restriking wave cannot be predicted, but various possibilities are considered below.

(i) *Arc resistance varying inversely as the current.*—In this case the arc voltage will be a constant (V_A). Since the resistance will be rapidly increasing towards infinity as the current approaches zero, the current will no longer be a true sine wave, but will have its slope increased at the zero in the ratio $(V_A + E)/E$, where E is the value of the system-voltage recovery-wave at the instant of interruption.

At the first zero in the cycle shown in Fig. 8, an attempt has been made to interrupt. As the current reaches zero, the arc voltage commences to fall along a sine wave, and then builds up in the reverse direction, until a value is reached sufficient to restrike the current. This value will be higher than the previously existing

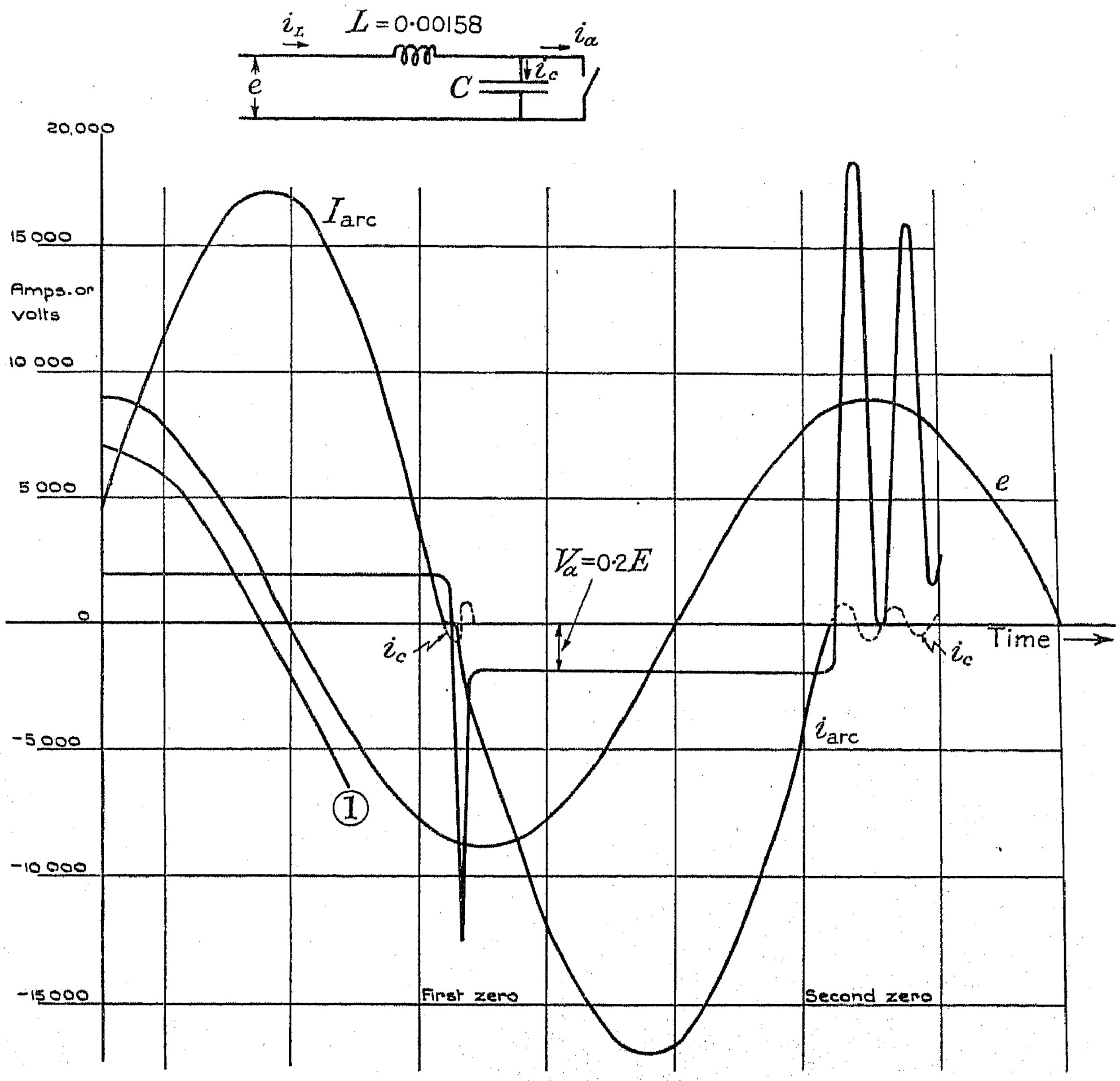

FIG. 8.

$$i_L = i_{arc} + i_c$$
$$C = 28\ \mu F$$
$$e = 9\,000 \sin \omega t$$
Curve (1), which for the sake of clearness is not continued, represents $L(di_L/dt) = e -$ (voltage across breaker).

arc voltage, since a finite time-interval has existed for the arc gap to increase its electric strength. When breakdown occurs, the voltage will rapidly fall to the normal arc-voltage value along a damped wave.

The fact that the arc voltage is not necessarily zero when the current becomes zero is explained by the flow of capacitance charging current, shown as part of a sine wave at the natural circuit frequency, which will reverse when breakdown occurs, and fall to approximately zero in a manner dependent on the arc characteristics during the breakdown period.

At the second zero (Fig. 8) interruption takes place and the full restriking oscillation appears across the breaker; this oscillation is of a damped sine form, owing to circuit resistance. The only difference between the two cases is then in the extent by which the arc space increases in electric strength during the period when the arc current is suppressed. If the increase is sufficient, interruption will occur, and the amplitude of the resultant voltage surge across the contacts will be $2(V_A + E)$. The rate of rise will be increased in the ratio $(V_A + 2E)/(2E)$.

For the case shown in Fig. 8, where the arc-voltage is 1 800 volts,

$$\text{Restriking peak} = (2E + V_A) \times (\text{Resistance damping factor})$$
$$= 19\,800 \times 0\cdot94 \text{ volts.}$$

Also, the current in the arc is given by

$$i_{arc} = \frac{9\,000}{2\pi f L}\Big[\sin 2\pi f(t - 0\cdot005) - 0\cdot2 \times 2\pi f(t - 0\cdot005) + 0\cdot246\Big]$$

where f is the system frequency. The restriking oscillation frequency as shown in the diagram is considerably lower than that usually obtained in practice.

The arc resistance being assumed great in the zero region, it might be thought that the e.m.f. would be almost in phase with the current, whereas it is really 72° lagging at this instant with the relative values of arc voltage and applied e.m.f. shown, and has in consequence 95 per cent of its maximum value. In order to affect appreciably the value of the restriking voltage, this angle must be reduced considerably, which necessitates the arc resistance being higher than is normal with oil circuit-breakers throughout the cycle, and not only in the region of the current zero.

In actual practice the resistance of an arc does not become infinity, but has been shown to fall in the current-zero region with a rapidly changing current, as is the case for alternating current. This fall, however, often commences so near the actual zero that its effect is only to allow the arc to act as a high shunting resistance to the recovery oscillation, which will show in an oscillograph as damping of the initial part of the wave.

If the circuit is more complicated and has two natural oscillating frequencies, the increased amplitude due to arc voltage will be distributed between the two superimposed waves, and the effect may be to increase or decrease the resultant rate of rise according to the relative frequencies and manner of distribution.

Fig. 9 shows the theoretical restriking wave for an assumed circuit together with the wave obtained on the same circuit assuming an arc voltage of one-half peak line volts, and with the consequent increase in amplitude distributed between the waves in the ratio of their theoretical amplitudes. The average rate of rise is reduced by 45 per cent.

(ii) *Arc resistance suddenly approaching infinity before the current reaches a natural zero.**—In this case the current in the arc will fall to zero at a very high rate, causing a discontinuity in the wave. The flow of energy cannot, however, be stopped and will be deflected into the capacitance of the system adjacent to the breaker, raising its voltage and consequently that across the contacts [see Figs. 10(A) and 10(B)].

The voltage peak produced in the condenser will have the same polarity as the previous arc voltage, and from energy considerations will be

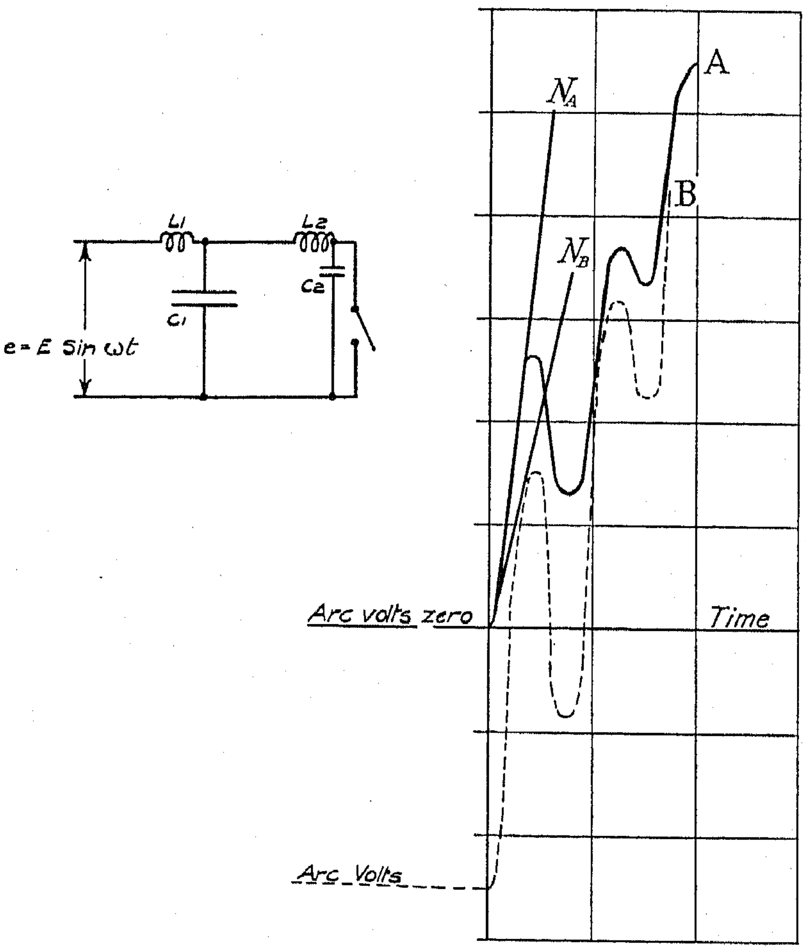

FIG. 9.—Effect of arc voltage on double-frequency restriking wave.

A. Arc voltage = 0
B. Arc voltage = ½ (Peak line voltage)

$$\frac{\text{Slope of } N_A}{\text{Slope of } N_B} = \frac{\text{Rate of rise of restriking voltage for A}}{\text{Rate of rise of restriking voltage for B}} = 1\cdot82$$

$$e_{max.} = \sqrt{\left(\frac{LI_c^2}{C}\right)}$$

neglecting arc voltage, for the circuit shown (I_c = current at " cut off "). The restriking wave can then be represented by the equation

$$e_r = E(1 - \cos \omega t) - e_{max.} \sin \omega t$$

where ω = natural frequency of circuit (in radians). This curve has been plotted for an 11-kV system with earthed fault and neutral, having a short-circuit current of 12 800 amps. and natural frequency of 50 000 cycles per sec. [Fig. 10(A)]. The natural rate of rise of this circuit (N_1) would be 2 050 volts per microsecond, but with " cut-off " assumed at a current value of 10 amperes the average rate (N_2) is reduced to 1 850 volts per microsecond, while the peak voltage appearing across the contacts has risen from 2 to 2·13 times the phase-neutral peak value.

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* See References (14), (15), (17), and (19).

Fig. 10(B) is for a circuit of the same natural frequency and rate of rise, but with a short-circuit current of 3 200 amps. Cut-off at 10 amps., however, in this case increases the rate of rise to 2 350 volts per microsecond, and the peak voltage to 3·43 times the phase-neutral peak. The restriking wave N_2 is considerably more severe than previously, since the average rate of rise is not only greater but is maintained for a longer period.

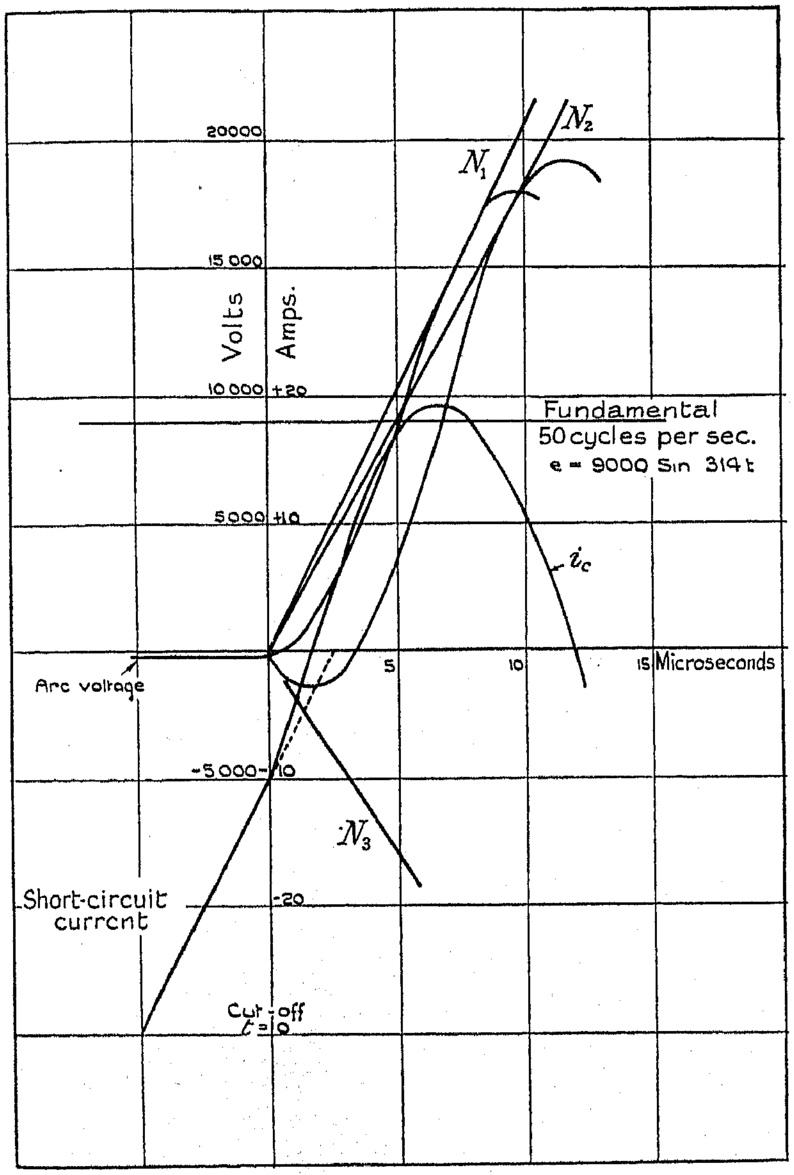

Fig. 10(A).
$N_1 = 2\,050$; $N_2 = 1\,850$; $N_3 = 1\,570$.

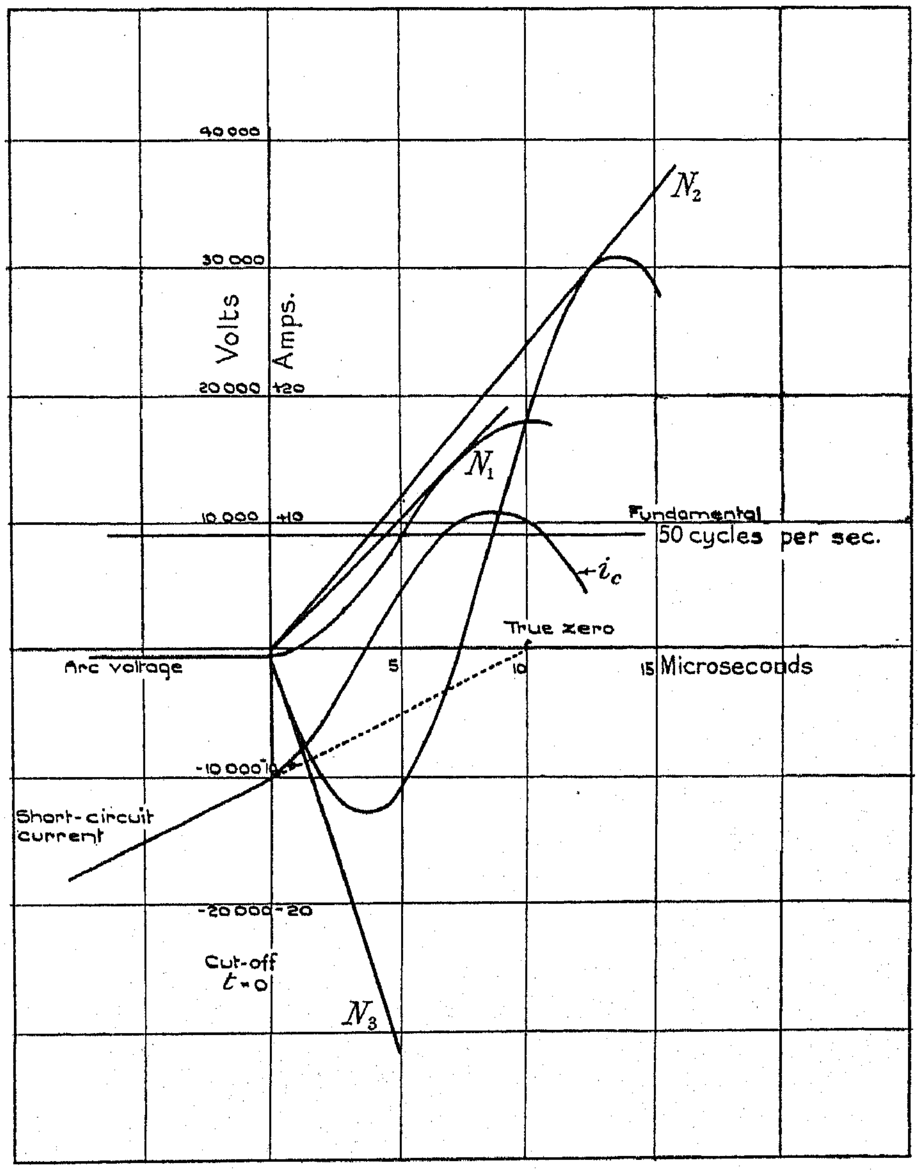

Fig. 10(B).
$N_1 = 2\,050$; $N_2 = 2\,350$; $N_3 = 6\,280$.

It therefore appears that the effect of cut-off of arc current may be to increase or decrease the natural rate of rise of the circuit, while the effects will be more severe the higher the frequency, the greater the cut-off value, and the greater the ratio L/C.

The excessive rates of rise that can be produced on the reverse wave (N_3) are of little importance, since failure due to this, provided it occurs prior to the true current-zero, will not necessarily result in an additional half-cycle of arcing. Since the reverse oscillations commence immediately at their maximum slopes, these latter serve to show the difficulty of the process of cutting off an arc prematurely.

(iii) *Arc resistance increasing at a rate greater than the increase of the current.*—In this event the arc voltage will increase towards the current zero, and the effect on restriking waves will be the same as in case (i), but may be greater in value as higher arc voltages will be obtained just prior to the current zero.

(iv) *Arc resistance finite after current zero.**—In this event a leakage current will continue to flow in the arc, given by

$$i_{arc} = \frac{\text{Instantaneous restriking voltage}}{\text{Instantaneous arc resistance}}$$

The restriking wave will commence at the instant of zero current, but will be of damped form, as indicated in Fig. 11, where curve (1) represents critical damping in which no oscillations occur and is of the form

$$e = AE(1 - B\epsilon^{-\alpha t} - C\epsilon^{-\beta t})$$

curve (2) is a damped sinusoidal wave of form

$$e = AE(1 - B\epsilon^{-\alpha t}\cos\beta t - C\epsilon^{-\alpha t}\sin\beta t)$$

while (3) is undamped. These curves are calculated for constant arc resistances, while curve (4) represents approximately the restriking wave associated with a varying resistance as shown in (5); curve (7) represents the leakage current associated with this latter wave. It will be seen that the rate of rise, frequency, and peak voltage, may be very considerably reduced by the passage of quite a small current.

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* See References (2), (14), and (16).

Critical damping occurs when $R < \sqrt{[L/(4C)]}$, and the damping will be greater the less the values of R or C/L. Consequently, high-frequency circuits will be damped more in proportion than lower frequencies for a given arc characteristic and given possible kVA.

(5) METHODS OF SOLUTION FOR RATES OF RISE.

For the purposes of these calculations, electrical plants may be divided into two categories: (*a*) those possessing lumped constants, and (*b*) those possessing distributed constants. By (*a*) is meant circuits in which phenomena cannot be regarded as taking place instantaneously in all parts, i.e. circuits possessing some considerable degree of length. Many systems having transmission lines of several miles' length can, however, be solved with sufficient accuracy by suitable lumping of their distributed values, it being usually impracticable to obtain the circuit constants with a sufficient degree of accuracy to justify the complete solution, except for very long lines.

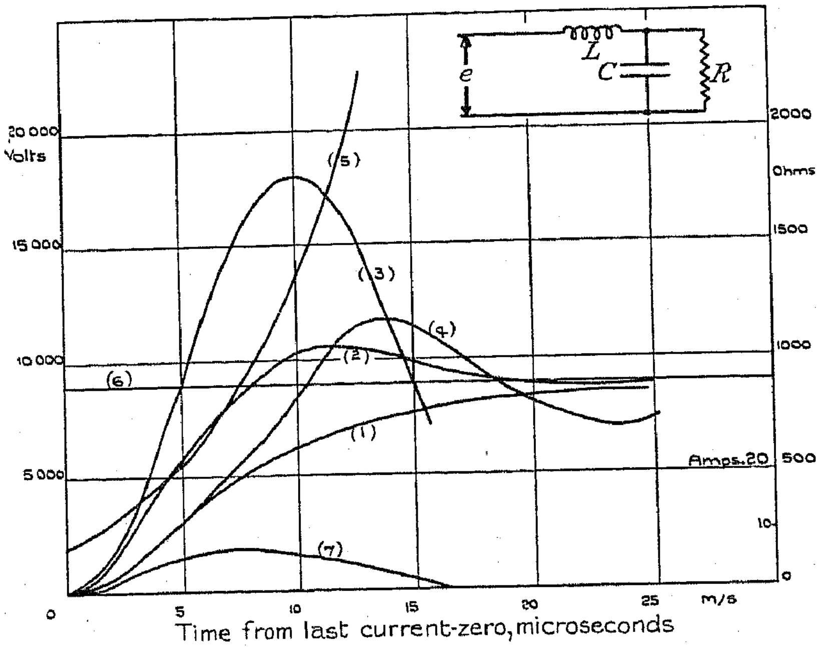

FIG. 11.—Effect of leakage-current damping circuit.

$L = 0\cdot00158$ henry; $C = 6\,350\ \mu\mu$F.

(1) Arc resistance 200 Ω, restriking rate 650 volts per microsecond, frequency zero.
(2) Arc resistance 1 000 Ω, restriking rate 1 150 volts per microsecond, frequency 41 600.
(3) Arc resistance infinite, restriking rate 2 050 volts per microsecond, frequency 50 000.
(4) Approximate curve for arc resistance varying as shown in (5); restriking rate 920 volts per microsecond; frequency (first wave) 36 000, (subsequent waves) 50 000.
(5) Arc resistance associated with (4) and (7).
(6) $e = V \sin(2\pi f t) = 9\,000 \sin 314t$.
(7) Arc current associated with (4) and (5).

Three-Phase Faults.

The relative rates of rise of the first and subsequent phases to clear will depend on the voltages and circuit frequencies corresponding to the various types of faults involved. The frequency for the second phase to clear of a 3-phase earthed fault on an earthed-neutral system, if one phase clears before the other, will be composite. Referring to the numerical example on page 331, in which the frequency for the first phase is 50 000 cycles per sec., the two frequencies for the second phase of this system would vary from 41 000 and 71 000 when the earth capacitance is zero, to 50 000 and 50 000 (in reality one oscillation only) when the neutral capacitance becomes zero. Over this whole range, the voltages associated with the two oscillations will be very nearly equal, and the restriking rate will vary from that for the first phase by only a negligible amount. If the oscillation of the first-phase restriking wave is itself composite, the analysis for the second phase becomes too complicated to give a satisfactory solution, allowing for the inherent inaccuracies in the computation of the constants. Although a general statement cannot, therefore, be given as to the exact ratio of the first and second phase restriking rates, as a first approximation they may be considered equal.

When either neutral or fault or both are not earthed, the restriking-voltage magnitude of the first phase will be $0\cdot866$ times that of the remaining phases, which will clear simultaneously. This second wave will be composed of three or more frequencies, but any increase of restriking rate due to these two causes will be offset by the fact that it appears across two phases.

It is therefore reasonable to calculate the first phase to clear for 3-phase faults, this being considerably the easiest to obtain.

Solution for Lumped Constants.

(*a*) *Determination of physical constants of system.*—Considering first the determination of the reactance, by "lumped" methods, the reactance to neutral of the system at the point of fault will be required; and, if the fault is not at the circuit breaker under consideration, the distribution of the reactance on either side of the breaker must also be determined. Different types of faults will require different reactances, but if the phase-neutral value is used the factor K_g given later covers this variation.

Dealing next with the determination of the capacitance of generators; in circuits comprising only a generator, circuit breaker, and short cables, the natural frequency or frequencies of the generator will be the determining factor, and the only satisfactory solution is to obtain the circuit frequencies by experimental methods, unless the generator equivalent-circuit can be obtained from the manufacturer. Where reactors and transformers are interposed between the generator and the breaker, the generator capacitance will be very large in comparison with the capacitances of the stationary plant, and may be represented as a short-circuit to the capacitance.

The capacitance of transformers can also only be determined by the designers or by experiment, but an approximate value of 30 000 cycles per sec. for the natural frequency may be used in the absence of specific data. The capacitance can then be obtained from the formula

$$f = \frac{1}{2\pi\sqrt{(LC)}}$$

The value thus obtained for C will normally be on the low side, giving the highest probable restriking rate.

The capacitances of all types of reactors are so low that they may be neglected. In the case of metal-clad reactors, the bushings must, however, be included.

To determine the capacitances of transmission lines or cables, let $3C_1$ = capacitance to neutral of each phase, and let C_2 = capacitance to earth of each phase; then, on an earthed-neutral system, for the first phase to clear of a 3-phase earthed fault the effective capacitance is given by $C = 2C_1 + C_2$. For the first phase to clear of a two-phases-to-earth fault on an earthed-neutral system, the circuit gives two frequencies:—

$$\frac{1}{2\pi\sqrt{[L(C_3 + 2C_1)]}} \quad \text{and} \quad \frac{1}{2\pi\sqrt{(LC_3)}}$$

where $C_3 = C_1 + C_2$.

Hence the effective capacitances are $(C_2 + 3C_1)$ and $(C_1 + C_2)$, giving one frequency higher and one lower than for the 3-phase case.

(*b*) *Solutions for Frequency of Simple Circuits.*

For stationary plant,

$$f = \frac{1}{2\pi\sqrt{(LC)}}$$

While for synchronous plant,

$$f = \frac{1}{4\sqrt{(LC)}}$$

Where there are two oscillating circuits, one on either side of the breaker, the solutions may be obtained separately and the restriking waves added. Where the two oscillations are on one side of the breaker, they should be solved by the methods given on page 334.

(*c*) *Determination of Voltage Associated with System Fault.**

The voltage to be associated with a fault is given by

$$V\ \text{(phase-neutral)}\sqrt{2}K_gK_\delta K_q$$

where K_g is a factor dependent on the type of fault, K_δ depends on the voltage decrement due to change in excitation, and K_q on quadrature reactance. The voltage will oscillate to twice this value before settling down, the peak value of the first high-frequency wave being, therefore,

$$2\sqrt{2}V\ \text{(phase-neutral)}\ K_gK_\delta K_q$$

Values of factors K_g, K_δ, and K_q.—We have:—

X_g = zero phase-sequence reactance;
X_q = reactance of system using quadrature sub-transient of synchronous plant;
X_d = reactance of system using direct sub-transient of synchronous plant;
K_g = 1·0 for a one-line-to-earth short-circuit;

$$K_g = \frac{2\sqrt{3}(X_q^2 + X_qX_0 + X_0^2)^{\frac{3}{2}}}{S_d''(2X_q + X_0)^2 + X_0(2X_q + X_0)(X_q + 2X_0)}$$

for a two-lines-to-earth short-circuit;

K_g = 1·73 for a line-line short-circuit or, approximately, for the first phase to clear of a two-lines-to-earth short-circuit on an impedance earthed or non-earthed system;

$K_g = \dfrac{3X_0}{X_q + 2X_0}$ for any 3-phase short-circuit;

K_g = 1·5 for a 3-phase short-circuit with either neutral or fault earthed;

$K_\delta = \dfrac{\text{A.C. component of current at clearing}}{\text{Initial a.c. component of current}}$;

K_q = 1·0 for all 1-phase short-circuits;
K_q = 1·0 for all two-lines-to-earth short-circuits;
$K_q = X_q/X_d$, for all 3-phase short-circuits.

In addition to the K_δ factor mentioned above, which decreases the magnitude of voltage associated with the oscillation at the time of clearing, there is a further decrement factor to be applied to the high-frequency oscillations themselves, due to resistance damping. This factor is approximately 0·94, the ratio of the slope of the tangents from the zero time and voltage axes to the damped and undamped waves.

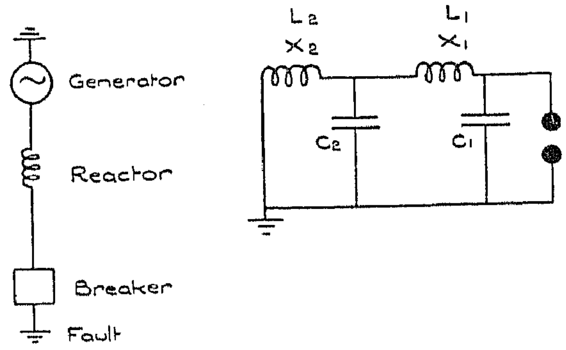

FIG. 12(A).

(*d*) *Determination of Distribution of Voltage Between Oscillations.*

The case set out in Fig. 12(A) gives $\dfrac{X_1}{X_1 + X_2}E$ associated with high-frequency oscillations of reactor and $\dfrac{X_2}{X_1 + X_2}E$ associated with low-frequency oscillations of generator. This is approximately correct, since the generator capacitance is very large. The method given on page 334 must be used when the difference in values is not very great or when a more accurate solution is desired.

Turning to Fig. 12(B), in this case there are three frequencies; two as in the above example, and one other associated with X_3/C_3. The voltages will be (approximately):—

$\dfrac{EX_1}{X_1 + X_2 + X_3}$ associated with generator oscillations (frequency f_1).

$\dfrac{EX_2}{X_1 + X_2 + X_3}$ associated with reactor X_2 oscillations (frequency f_2).

$\dfrac{EX_3}{X_1 + X_2 + X_3}$ associated with reactor X_3 oscillations (frequency f_3).

In the calculation of such a system, the generator frequency will often be so low compared with f_2 and f_3 that it may be neglected.

---

* See Reference (6).

(e) Determination of Rate of Rise of Restriking Voltage.

When the fundamental wave has a frequency of f cycles per sec., the maximum average rate of rise—or the slope of the tangent to the wave from the point representing zero time and voltage—becomes

$$N = 4 \cdot 31 V \text{ (phase-neutral)} \sqrt{2K_\delta K_g K_q f} \times 10^{-6} \text{ volts per microsecond.}$$

The factor 4·31 allows for the resistance damping of the high-frequency oscillation.

If the 0·94 factor is omitted, the factor will be 4·55.

Composite-frequency circuits.—When the effect of the lower frequency f_2 is small, i.e. when the f_2 component is of much lower frequency and/or amplitude, the following formula may be used to calculate the combined rate of rise (N) of the two waves. Let f_1 be associated with x per cent voltage and high-frequency oscillations, and f_2 be associated with y per cent voltage and low-frequency oscillations.

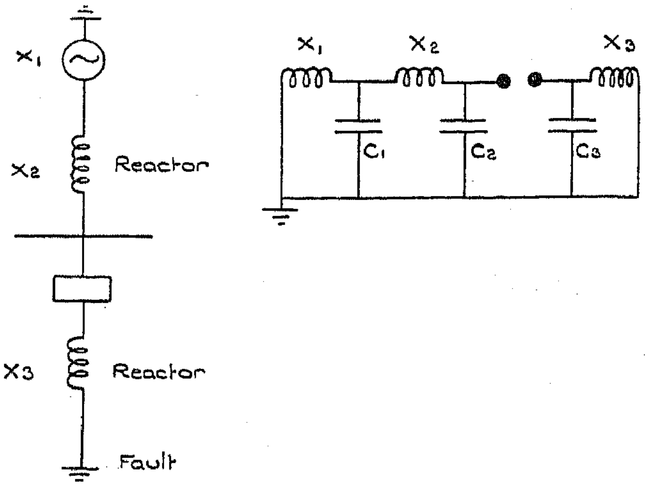

FIG. 12(B).

Then

$$N = V\text{(phase-neutral)} \sqrt{2K_g K_q K_\delta 10^{-6} f_1} \left[4 \cdot 31 \frac{x}{100} + 2 \cdot 71 \frac{y}{100} \left(1 - \cos \frac{133^\circ f_2}{f_1} \right) \right]$$

When the ratio of the rates of rise of the two oscillations is of the same order, the curve should be drawn out and the solution obtained graphically.

Correction of displacement.—When a d.c. component is present in the current wave, the applied voltage E will not be a maximum when the current passes through zero, owing to the angular displacement along the time axis of the zero point. A fully displaced wave will reduce the rate of rise to zero for the high-frequency oscillations. A correction may be applied to the theoretical rate for any particular short-circuit; this correction is obtained from measurements of the magnetic oscillogram, and is calculated in the following way. Let the current ordinates of the last-cycle peaks be x and y. The d.c. component is $\frac{1}{2}(x - y)$, and the ratio of displacement is $(x - y)/(x + y) = \sin \phi$ (say). Then the correction factor for the rate of rise is $\cos \phi$.

(6) METHODS OF SOLUTION FOR MORE COMPLICATED CIRCUITS.

When the constants of various plant units in series are being lumped, they should be arranged as Π or T circuits, to simulate the multi-frequency conditions which will occur in practice. The circuits on either side of the breaker [see Fig. 12(B)] should be solved separately, and the resultant waves added to give the total restriking voltage.

Rigid Solution for Frequency and Voltage Associated with Oscillations.

Consider the circuit represented by Fig. 12(A). We have

$$e = \int \frac{i}{C} dt = L\frac{di}{dt} = Lpi$$

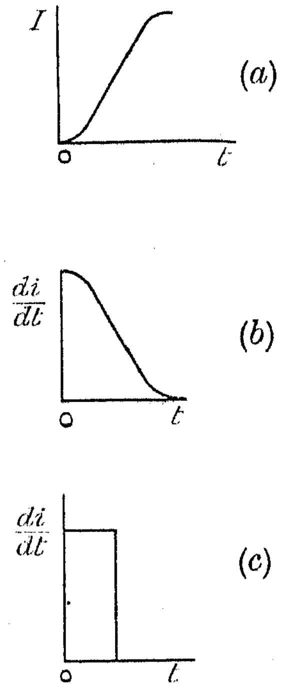

FIG. 13.

The capacitance reactance is $1/(pC)$ and the inductive reactance is pL. Also the impedance of the circuit is given by

$$Z = \cfrac{1}{pC_1 + \cfrac{1}{pL_1 + \cfrac{1}{pC_2 + \cfrac{1}{pL_2}}}}$$

$$= \frac{p(L_1 + L_2) + p^3(L_1L_2C_2)}{p^4(L_1L_2C_1C_2) + p^2(L_1C_1 + L_2C_1 + L_2C_2) + 1}$$

Now since the current (negative) starts off as in Fig. 13(a), di/dt commences as in Fig. 13(b), or initially may be regarded as equivalent to Fig. 13(c). Also, since i may be written as $\int \frac{di}{dt}$,

$$i = \frac{1}{p}\frac{di}{dt} = \frac{1}{p}\mathbf{1}$$

where $\mathbf{1} = f$(unity), as indicated by Fig. 13(c).

Then

$$e = iZ = \frac{Z}{p}\mathbf{1}$$

$$= \frac{(L_1 + L_2) + p^2(L_1L_2C_2)}{1 + p^2(L_2C_2 + L_1C_1 + L_2C_1) + p^4(L_1L_2C_1C_2)}\mathbf{1} \quad (1)$$

Solving the denominator for roots ω_1^2 and ω_2^2 by equating to zero, and converting to partial fractions,

$$e = \frac{A}{(p^2 + \omega_1^2)}\mathbf{1} + \frac{B}{(p^2 + \omega_2^2)}\mathbf{1} \quad . \quad . \quad . \quad . \quad (2)$$

where

$$A = \frac{\omega_1^2 L_1 L_2 C_2 - L_1 - L_2}{L_1 L_2 C_1 C_2(\omega_1^2 - \omega_2^2)}$$

$$B = \frac{L_1 + L_2 - \omega_2^2 L_1 L_2 C_2}{L_1 L_2 C_1 C_2(\omega_1^2 - \omega_2^2)}$$

Solving (2),

$$e = \left[\frac{A}{\omega_1^2}(1 - \cos \omega_1 t) + \frac{B}{\omega_2^2}(1 - \cos \omega_2 t)\right]\mathbf{1}$$

commencing at $t = 0$, whence A/ω_1^2 and B/ω_2^2 give the amplitudes of the waves, and ω_1 and ω_2 the frequencies in radians. The actual value of e is obtained by substituting the initial value of di/dt for $\mathbf{1}$, which represents the conditions for unity di/dt applied at $t = 0$.

ACKNOWLEDGMENTS.

Full use has been made of the papers referred to in the list of references given below, and in particular that of Messrs. Park and Skeats, upon whose work the mathematical section of this paper is based.

In addition, the author wishes to thank Messrs. W. A. Coates and C. Dannatt for their helpful criticism. His thanks are also due to the Metropolitan-Vickers Electrical Co., Ltd., and the General Electric Co., Schenectady, U.S.A., for permission to publish this paper.

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APPENDIX.

CIRCUITS WITH DISTRIBUTED CONSTANTS.

The process of solving distributed circuits, which should be employed in connection with long lines, comprises the imposing of a negative current on the system flowing from the breaker terminals, of the same magnitude and frequency as the short-circuit current. The net result in the system is therefore zero current, representing interruption of flow.

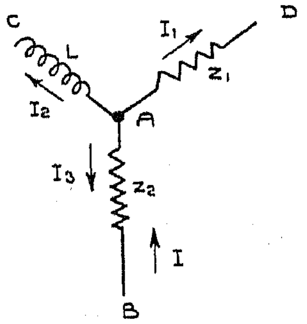

FIG. 14.

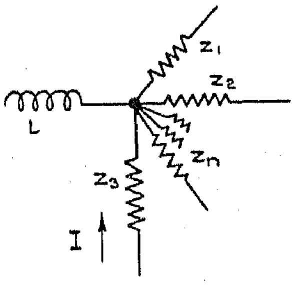

FIG. 15.

Owing to the transient nature of the restriking waves for the short period of time during which they take place, the imposed short-circuit may be regarded as constant ($di/dt \rightarrow 2\pi f I_{peak}$), as in the previous case. At 1 500 microseconds on a 50-cycle system the error in this assumption becomes about 11 per cent, and rapidly increases thereafter.

If a certain value of di/dt is impressed on a transmission line of surge impedance $\sqrt{(L/C)}$

$$\frac{de}{dt} = \frac{di}{dt}\sqrt{\left(\frac{L}{C}\right)}$$

When a junction occurs between lines of different surge impedances, reflections occur, of such a nature that the current flowing towards the junction is equal to that flowing from it. Referring to Fig. 14, which represents two transmission lines and a transformer meeting at A,

$$I = I_1 + I_2 - I_3$$

$$I_2 = \int \frac{e}{L} dt; \quad I_1 = \frac{E}{Z_1}; \quad I_3 = \frac{-E + V_{AB}}{Z_2}$$

where E = voltage of A above earth due to impressing current I on the circuit flowing from $B (E = IZ_2)$. Then

$$I = \frac{E}{Z_1} + \frac{E - V_{AB}}{Z_2} + \int \frac{e}{L} dt$$

$$\frac{di}{dt} = \frac{1}{Z_1}\frac{de}{dt} + \frac{1}{Z_2}\frac{de}{dt} - d\frac{(V_{AB})}{dt}\frac{1}{Z_2} + \frac{e}{L}$$

Now di/dt is a known constant K, and

$$K = \frac{Z_1 + Z_2}{Z_1 Z_2}\frac{de}{dt} - K + \frac{e}{L}$$

Thus

$$2K = \frac{Z_1 + Z_2}{Z_1 Z_2}\frac{de}{dt} + \frac{e}{L}$$

Similarly, for the circuit of Fig. 15,

$$2K = \left(\frac{1}{Z_1} + \frac{1}{Z_2} \cdots + \frac{1}{Z_n}\right)\frac{de}{dt} + \frac{e}{L}$$

The method of procedure to be followed is now to determine K for the given circuit, and to solve for the various reflections at each extremity and junction of the lines. At the open circuit-breaker, 100 per cent reflection of the voltage and current waves will occur, the former being reflected positively and the latter negatively. At short-circuits, voltage waves will be reflected 100 per cent negatively and current waves 100 per cent positively. To obtain the extent of the reflections at reactances and impedances the appropriate equation must be written down.

The initial conditions are such that inductances may be regarded as open circuits, reflecting voltage-waves 100 per cent positively; while finally they will behave as short-circuits, reflecting voltage-waves 100 per cent negatively. This enables a rapid check to be made on the equations at $t = 0$ and $t = \infty$.

In the solving of an actual case, a table of waves generated at the various junctions and terminals should be compiled. Such a table is given in Fig. 17 for the circuit of Fig. 16. The bracketed letters give the initiation time for each wave in terms of the wavelengths of the lines PQ(t_1) and QS(t_2), as given by their lengths divided by the propagation velocity (about 1 000 ft. per microsecond for transmission lines and 300–500 ft. per microsecond for cables).

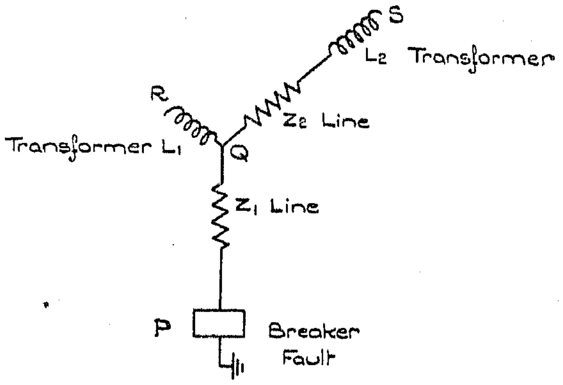

FIG. 16.

Applying the short-circuit di/dt at the breaker P of value K, the voltage wave (1) will be $e = KZ_1 t$, and the voltage at Q commencing at time t_1 will be given by the equation

$$\frac{Z_1 + Z_2}{Z_1 Z_2}\frac{de}{dt} + \frac{e}{L_1} = 2K$$

Hence, for the initial conditions $t = t_1$, $e = 0$,

$$e_Q = 2KL_1\left[1 - \epsilon^{\left(\frac{-Z_1 Z_2}{Z_1 + Z_2} \cdot \frac{t - t_1}{L_1}\right)}\right]_{t > t_1} \quad . \quad (2, \text{Fig. } 17)$$

and therefore,

$$\frac{de_Q}{dt} = A\epsilon^{-Bt}$$

A and B being constants.

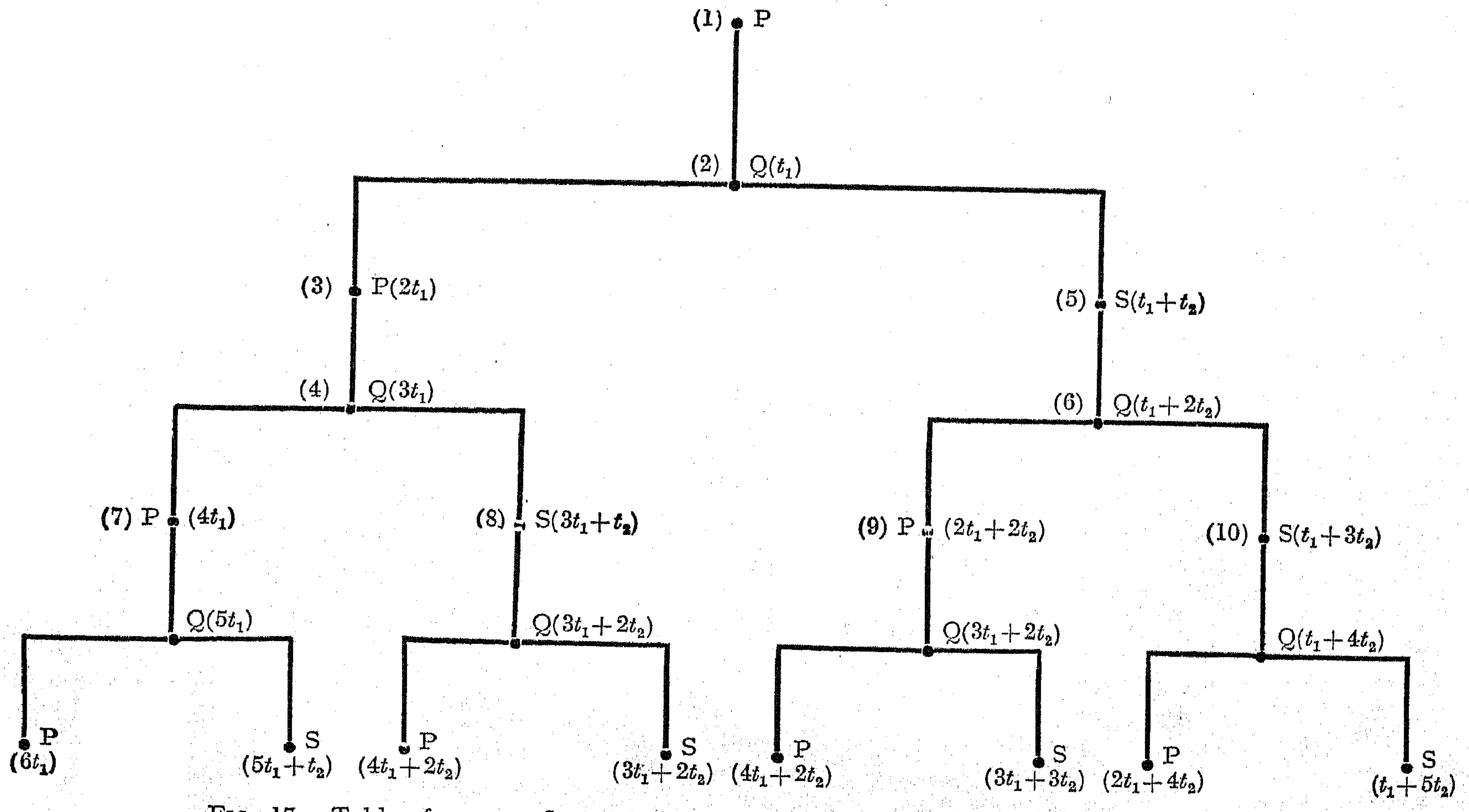

FIG. 17.—Table of waves reflected in circuit of Fig. 16, with their commencement times.

Hence di/dt towards S is $A\epsilon^{-Bt}/Z_2$. The equation for e at S is then, assuming $t > (t_1 + t_2)$

$$C\epsilon^{-Bt} = \frac{de_S}{dt} + \frac{e}{D}$$

where C and D are constants.

Hence

$$e_S = [F\epsilon^{-G(t-t_1-t_2)} - H\epsilon^{-J(t-t_1-t_2)}] \quad . \quad (5, \text{Fig. } 17)$$

where $t > (t_1 + t_2)$, $G \neq J$, and F, G, H, and J are constants. If $G = J$, we have

$$e_S = M(t - 1)\epsilon^{-N}$$

where M and N are constants. The wave reflected back towards Q is therefore (5) — (2). Thus a new equation is obtained for the voltage at Q and for the wave passing on to the breaker P, where the change in voltage will be twice that of the returning wave, since the latter will be reflected 100 per cent positively.

This form of solution is used for all voltage waves of appreciable magnitude until such time as the addition of further reflections will not increase the maximum average rate of rise of restriking voltage. This is best determined from a graphical summation of all reflections affecting the point P, and from which the rate of rise can be readily measured.

DISCUSSION ON

"THE INHERENT INSTABILITY OF SYNCHRONOUS MACHINERY."*

Prof. E. L. E. Wheatcroft (*communicated*): I have read the paper with very great interest and think it worth while to compare the authors' results with my own.†

The mathematics are necessarily involved, and, since the sign of the damping torque involves the difference of quantities which are small compared with the full-load torque, numerical calculation can only be approximate. In the formulæ given below I have endeavoured to simplify the calculation by combining damper resistance, leakage reactance, etc., into a single assumption that the change of flux lags behind the change of demagnetizing or cross-magnetizing current. Let i_1, i_2, be respectively the long-magnetizing and cross-magnetizing changes in armature current, and let ψ_1, ψ_2, be the changes in long and cross flux respectively. Then we may write

$$\psi_1 = k_1(i_1 - \sigma_1 di_1/dt)$$
$$\psi_2 = k_2(i_2 - \sigma_2 di_2/dt)$$

I think that this assumption is valid for low values of hunting frequency (3 or 4 cycles per sec.).

If n be the number of effective turns, and l the total leakage self-inductance per phase, we write for short

$$L_1 = l + nk_1, \quad s_1 = \sigma_1 nk_1,$$
$$L_2 = l + nk_2, \quad s_2 = \sigma_2 nk_2,$$

and

$$z^2 = r^2 + \omega^2 L_1 L_2$$

Also let V_1, V_2, be the components of "terminal e.m.f." (terminal P.D. corrected for armature resistance) in phase and in quadrature respectively with the "internal e.m.f."; and let I_A, I_B, be the load and magnetizing components respectively of the armature current. Then the critical condition for damping works out as follows:—

$$b\omega^2 z^4 + \omega^2 s_1(\omega L_2 V_2 + I_A r^2)^2 + \omega^2 s_2(\omega L_1 V_1 + I_B r^2)^2 >$$
$$(V_1 - \omega L_2 I_B)^2 r(\omega^2 L_1^2 - r^2 + r\omega^2 s_1)$$
$$+ (V_2 - \omega L_1 I_A)^2 r(\omega^2 L_2^2 - r^2 + r\omega^2 s_2)$$

The terms on the left-hand side being those which contribute to stability, and those on the right-hand side to instability.

V_2 depends, of course, on the cross-magnetizing effect of the load current I_A, and has the same sign. Thus the load only appears in the formula as a square term, and the balance of damping is the same (other things being equal) for a generator as for a motor. I_B is positive when the machine is "under excited."

The formula has sufficient flexibility to take account of the effects of saturation. V_1, V_2, can be determined in terms of I_A and I_B in accordance with usual machine theory, and r, l, can be found in the usual way. b represents the "rotation" damping due to windage and, if necessary, the shaft load: it is measured as the additional torque (per phase) due to increase in angular velocity, and must be expressed in

watt-sec./radian per radian/sec.

nk_1, nk_2, σ_1, σ_2, include all the effects of amortisseur and eddy currents in and round the poles. With solid poles the values can only be determined experimentally, but with laminated poles and suitable amortisseur circuits it will be possible to calculate them from the dimensions. The effect of saturation must be taken into account in the values of k_1, k_2.

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* Paper by Dr. J. C. PRESCOTT and Dr. J. E. RICHARDSON (see vol. 75, page 497).

† *Engineering*, 1934, vol. 137, pp. 616 and 642. The symbols employed in the present communication are identical with those used in the previous paper, except that I_A, I_B, are here substituted for A, B, respectively.

$I_A r^2$ and $I_B r^2$ are usually small.

In a symmetrical machine $L_1 = L_2 = L$, say, and V_2 is then approximately equal to $\omega L I_A$. The formula then reduces approximately to

$$b\omega^2 z^4 + \omega^6 s_1 L^4 I_A^2 + \omega^4 s_2 L^2 V_1^2 > (V_1 - \omega L I_B)^2 r(\omega^2 L^2 - r^2 + r\omega^2 s_1)$$

In a machine which is critically damped with no field-damping or amortisseur

$$b\omega^2 z^4 = (V_1 - \omega L I_B) r(\omega^2 L^2 - r^2)$$

Such a machine will not in general be improved by adding polar damping (s_1) only, except at such loads that

$$\omega^4 L^4 I_A^2 > (V_1 - \omega L I_B)^2 r^2$$

$$I_A > \frac{(V_1 - \omega L I_B) r}{\omega^2 L^2}$$

which may easily be of the order of full load, unless the rotation damping (b) increases with the load.

Dr. J. C. Prescott and **Dr. J. E. Richardson** (*in reply*): We have compared Prof. Wheatcroft's treatment of the coefficients of inherent instability with that published in the paper, and the following points of similarity emerge.

In Prof. Wheatcroft's expressions $\sigma_1 k_1$ is equivalent to our $\lambda\beta_1/(N\Omega)$, while k_1 is our $\lambda\gamma_1/N$; thus his L_1 is our a and his s_1 is our $\lambda\beta_1/\Omega$.

We differ from him, however, in our determination of the flux along and across the axis in the disturbed position. Following Hopkinson, we have included a term, as explained on page 501 (vol. 75), to allow for the change in reluctance in the paths of the flux, due to the steady currents I_1 and I_2, when the rotor is disturbed. The inclusion of this flux would give terms proportional to $I_1\theta$ and $I_2\theta$ (if θ, the magnitude of the disturbance, is small) in the expressions for ψ_1 and ψ_2 respectively.

Even when this term is neglected, however, we have not been able to arrive at his expression for the negative damping torque. Working from equation (3) in his paper* and including L and s, we arrive at the same four equations of coefficients which we used in our own calculation of the components of the current induced by the disturbance of the rotor; they are stated at the foot of page 509 in the Appendix to our paper.

The values which we obtained for the current components differ, however, from those of Prof. Wheatcroft, notably in the expression for z^4 (our X_0^2). It would seem that Prof. Wheatcroft is either using an approximation different from ours (which occurs in the evaluation of R_1, R_2, R_3, etc., and is stated on page 509), or that he has seen some algebraic simplification which we have missed. As he says, the calculation of the damping torque is a difficult matter, since the terms which it contains are small compared with those composing the expression for the synchronizing torque: and therefore the final result obtained may well be influenced to a very considerable extent by the approximations used in arriving at it.

We have, however, compared our results for the positive electrical damping torque (see page 503 of our paper) with those obtained by Wennerberg, and find them to be identical. Unfortunately, the negative torque due to armature resistance in a machine fitted with dampers is not worked out by that author. Our equation (14) also agrees with that obtained by Steinmetz for an induction motor.

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* *Engineering*, 1934, vol. 137, p. 616.

DISCUSSION ON

"RESEARCH IN THE BRITISH POST OFFICE."*

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 5TH NOVEMBER, 1934.

Mr. A. J. Pratt: After perusing the description of the building, apparatus, and equipment, one can only reach the conclusion that the whole scheme is an admirable one in all respects. Moreover, it is certain that, being a Government scheme, quite apart from its revenue-earning capacity, it is run on economical lines.

One observes that quite a long period elapsed before the whole of the buildings, equipment, etc., reached the completion stage. This may have been due to some extent to the inborn antipathy of the average British citizen to incur or sanction national expenditure for research work. He demands facilities for long-distance transmission, including universal telephone conversation with the same clarity of articulation whatever the distance; he asks for underground circuits in place of overhead wires, notwithstanding the technical difficulties involved in their provision; and so on. When he is told that research work on a comprehensive scale is essential for the progress of the telephone industry, he is indifferent to the need for expenditure on a fairly liberal scale for research work.

Provincial engineers realize the value of certain phases of research work in regard to the problems of the creeping of cables, the presence of gas in manholes, the electrolysis of cable sheaths, wireless interference, and carrier-wave transmission, as mentioned in the paper. The provincial engineer is also closely concerned with the teleprinter service, an efficient and cheap service which is superposed upon other services with no physical addition to the line plant.

Prof. E. W. Marchant: In the past, when some of the research students at the University of Liverpool have been engaged upon problems similar to those which were being studied at Dollis Hill, we have written to the Engineer-in-Chief of the Post Office, and he has arranged for the research student to go round the laboratories and to observe the methods in use there. I should like to thank the author and the staff of Dollis Hill for all they have done to help us in this way. I have been interested in the history of the development of the Dollis Hill Laboratory because it was started at just about the same time as our laboratory was built. The method which has been adopted for obtaining flexibility, i.e. having all benches connectible through connecting boards, is similar to the system we have used at the University of Liverpool.

My second point is with regard to the financial value of research, which I do not think has been stressed sufficiently in the past. The figures given in this paper are of great value. I saw an estimate the other day of the value of the researches that had been carried out by Edison; it ran into several hundreds of millions of dollars. If one looks at Faraday's work, which was so admirably demonstrated at the Faraday Exhibition* organized by the Institution, and realizes what has grown out of the discoveries that Faraday made, one does begin to see what an immense financial value there is in nearly all research work; and industrialists are recognizing this fact increasingly.

The last point I want to make is with reference to corrosion. We have had, for several years now, some cables and wires on the roof of this laboratory. I think the atmosphere is as bad as one can find in any part of Liverpool, on account of the smoke from the railway tunnel. The following figures, which I have already sent to the Engineer-in-Chief of the Post Office, cover a period of 2¼ years, and they provide a better testimonial for the atmosphere of S.W. Lancashire than the tests on galvanized wires that are given in the paper. We have tested three bronze wires: one, 0·05 in. diameter, has corroded to the extent of increasing in resistance by 4 per cent in 27 months; the second wire, 0·051 in. diameter, has increased in resistance by 5 per cent; and the third, 0·08 in. diameter, has increased in resistance by only 1 per cent. I am rather surprised at this result, as we have a lot of fog and smoke, but it is evident that one can get bronzes which will stand this atmosphere fairly well.

Mr. T. E. Herbert: I am glad to observe the tribute which the author pays to Mr. S. A. Pollock. I am glad, too, that the function of the Research Station as a training centre has been mentioned. In these days the old-fashioned method of training a young man by attaching him to a workman, to pick up in the course of a few years what he could, is hopelessly inefficient and extravagant. Quite a large number of graded courses have been provided at Dollis Hill, where men can be trained rapidly and efficiently. The weak spot in the old apprentice system lies in two facts: in the first place it is not every man who is capable of imparting instruction to others, although he may perform a particular function very efficiently himself; in the second place, there are many men who do their work in what is not an ideal way, and the results they achieve are obtained not because of, but in spite of, the methods which they adopt. A prolonged experience of the results of the training work at Dollis Hill makes me exceedingly enthusiastic, and I desire to see the plan still further extended. A description is given on page 137 of the "Construction Park," and the most casual inspection will demonstrate the value of the training which this makes possible. On page 138 (vol. 75) it is clearly demonstrated that the cost of the

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* Paper by Mr. B. S. COHEN (see vol. 75, p. 133).

* *Journal I.E.E.*, 1931, vol. 69, pp. 1329, 1385.

Research Station is more than justified by the savings which result, and I think it would be true to say that the Post Office gets better value for its money in this direction than any other organization in the world.

On page 139 (vol. 75) there is some discussion as to co-operation with other research organizations. I think that here there is probably a field for even greater advances. Practically all the large manufacturing concerns have research laboratories of their own, and there must be a considerable amount of overlapping. I am under the impression that this question is being considered and that the ultimate outcome may be to reduce the expenditure not only by the Post Office Research Section, but by the various manufacturers. It will, of course, be perfectly obvious that, so far as the manufacturers are concerned, the cost of their research stations must be provided for in the selling price of their products.

There are many instances in the paper of work done at Dollis Hill which has "led the world." One of the most interesting matters under experimental trial is the 2-wire repeater circuit; perhaps the author may be willing to tell us the stage which these experiments have reached. With regard to the acoustic laboratory (page 147, vol. 75), I should like to know what precautions have been taken to prevent this becoming infested by vermin.

One of the recent developments at Dollis Hill is a noise generator by means of which the efficiency of ordinary subscribers' apparatus can be measured at the exchange. This apparatus is on the point of being issued, and it will, I think, have profound effects in improving the efficiency of the telephone system as a whole. The invention of the 2-frequency signalling system (page 149, vol. 75) will alone serve to pay the cost of the Research Station for some years. Time was when the British telegraph system was a pattern imitated by the whole world. The apparatus designs have never been surpassed, and I think that we may well look forward to the day when precisely similar conditions will apply to telephone engineering generally.

Mr. H. R. Noble: On page 142 (vol. 75), under the heading "Dielectric Research," the author states that Aquadag electrodes have proved very useful in facilitating tests. Considerable research on dielectric properties is being carried out at Liverpool University, and about a year ago I made several experiments to test convenient electrodes. Results were obtained for the power factor of ebonite, using the following electrodes: brass plates, tin-foil and vaseline, tin-foil and Aquadag, Aquadag. The results were compared with those obtained using mercury as a standard. Above some 200 000 cycles per sec. Aquadag gave high results, while the figures obtained with the other electrodes formed a narrow zone, consistent with experimental error, giving a power factor of about 0·030, compared with the value 0·048 obtained for Aquadag at 1 megacycle per sec. Tin-foil attached with a smear of vaseline, and pressed, was chosen as the best substitute for mercury electrodes for practical testing. Corroborative tests were made on a glass specimen. The power-factor results were: at 1 megacycle per sec., tin-foil and vaseline 0·0045, Aquadag 0·0294; at 5 megacycles per sec., tin-foil and vaseline 0·00426, Aquadag 0·0884. The Aquadag is thus seen to be totally unreliable in the higher frequency range, but this discrepancy only arises in radio research. The results are of interest in view of the local work done.

Mr. B. S. Cohen (*in reply*): I very much appreciate the kind remarks of Mr. Pratt and Prof. Marchant. It is of interest to note that Prof. Marchant has adopted the same methods of obtaining flexibility in power-lead distribution through his laboratories as are in use at Dollis Hill. The work at Dollis Hill on the liability to corrosion of bronze wire confirms the results obtained by Prof. Marchant. This wire, and the alternative copper cadmium which the Post Office are using to a considerable extent, are very little liable to corrosion. Galvanized-steel wire, however, is quite another matter.

Mr. Herbert refers to co-operation with other research organizations and the desirability of obviating overlapping between the research laboratories of large manufacturing organizations and the Dollis Hill laboratories. As mentioned in the paper, this matter does receive careful consideration and there are committees in existence, attended by members of manufacturing concerns and officials of the Post Office Engineering Department, which deal directly with questions of development and research and their allocation. Mr. Herbert also refers to the developments in connection with 2-wire repeater circuits. The developments in this direction have now reached the stage of only requiring extended field trials to confirm the results obtained under research conditions. Mr. Herbert refers to the absorbent material used in the Acoustical Laboratory; this is a form of surgical lint, and appears to be quite unaffected by vermin.

I am indebted to Mr. Noble for the interesting information regarding the use of various types of electrodes in connection with measurements for determining the power factor of ebonite. As mentioned by Mr. Noble, our use of Aquadag electrodes has been confined to the low-frequency range, and the discrepancies shown only occur at frequencies of the order of 200 kilocycles per sec.

METER AND INSTRUMENT SECTION: CHAIRMAN'S ADDRESS

By Professor J. T. MacGregor-Morris, Member.

"THE TRAINING OF STUDENTS IN ELECTRICAL ENGINEERING AT AN INSTITUTION OF UNIVERSITY RANK."

(*Address delivered* 2nd *November*, 1934.)

Introduction.

Looking over the list of the previous chairmen of this Section, I notice at once that all are thoroughly practical men whose primary work has to do with the design, manufacture, or testing, of meters and instruments. It was with some diffidence, therefore, that I agreed to act as chairman of this Section, for I cannot lay claim to any of these qualifications. I have, however, had the privilege of contributing to the training—in the college stage—of electrical engineers, including one of our past-chairmen, Mr. F. C. Knowles, and I therefore felt it would not be inappropriate to accept the invitation. I appreciate the honour you have done me, and it will be my earnest concern to fulfil the duties of my office to the best of my ability.

I have chosen as the subject of this Address certain aspects of the college training of electrical engineers, and especially those parts of their training which should develop an interest in and love for electrical measurements and the instruments by which these measurements are made.

My enthusiasm for this subject was first stirred when my brother (Dr. D. K. Morris) and I as students at University College, London, came under the spell of Prof. J. A. (now Sir Ambrose) Fleming, whose earlier work on standards of e.m.f. and of resistance, and measurements of potential difference and resistivity, is now classical in electrical engineering. At University College there was also that pioneer in electrical measurements the late Prof. G. Carey Foster, a man of extraordinary modesty. In 1893 we attended his laboratory class of electrical measurements; this class gave a sure foundation for accurate electrical measurements, and I can never forget the evident joy it was to Carey Foster when we showed him some work thoughtfully done, in which the best had been got out of the instruments in use.

Forgive me if I appear to dwell too much on the personal side. My excuse must be that I am a firm believer that it is during one's student days that enthusiasm is either developed or quenched in this subject. It is only too often that one sees an electrical instrument handled with a lack of care and interest, which makes one feel that all the student is interested in is to get through the experiment with the least trouble and thought possible. He regards the instrument only as something which indicates a reading; as to why it works, the less he has to know about this the better.

College Training of Electrical Engineering Degree Students.

The essentials for a really living course of laboratory work are, in my view, the following. In the first place, the teacher must be enthusiastic about it. He must love to introduce each experiment to each student. Secondly, he must be intimately acquainted with each experiment. Thirdly, he must restrain himself from showing the student how to do the experiment, for this does not result in the student getting a practical grip of the experiment, but only in the student thinking how wonderful the teacher is! Fourthly, the list of experiments must be overhauled from time to time, say every 3 years, from two points of view: (*a*) as to subject matter, with the object of avoiding over-emphasis, or of neglect of certain branches; (*b*) as to possible improvements in existing experiments, as a result of increase of experience. And lastly, he should use every opportunity of visiting other laboratories. Personally, I owe much to such visits.

Wherever possible an experiment should be capable of being completed within 2 hours. I doubt whether an experiment that takes more than 4 hours is really worth doing, except in rare cases. Only in very exceptional cases should more than two students be engaged on the same experiment. In the case of experiments which can be carried out by individual students, it is much to be preferred that two students who otherwise work together should each carry through such experiments separately, and then should exchange.

I am inclined to believe that in the past too much emphasis has been placed on electromagnetic phenomena, at the expense of too little emphasis on phenomena connected with dielectrics.

The importance of the regular overhaul in subject matter of experiments may be better appreciated when one recalls the fact that almost all the following subjects have been introduced or greatly developed during the past 20 to 30 years: Production and detection of electric waves; thermionic valves; measurement of total flux of light by sphere or cube photometer; mercury-arc rectifier; copper-oxide rectifier; photo-electric cells; cathode-ray oscillographs; neon low-voltage lamp; gaseous discharge lamp of high efficiency; methods of study of the properties of dielectrics, e.g. by means of the Schering bridge. Many of these subjects include parts of that difficult but fascinating subject of electron physics.

Whilst considering the question of set experiments, I would draw attention to an article entitled "The Function of Laboratory and Design Work in the Education of Electrical Engineers," by Prof. Parker Smith.* This is a most valuable article dealing, as it does, primarily with laboratory experiments of a more or less routine nature, and I strongly recommend that it should be read by all interested in the training of electrical engineers.

The remarks which I, however, am making are the result of my work—in which I have been engaged for many years—of training electrical engineers, especially with a view to developing their interest in research and development.

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* *Engineering*, 1934, vol. 137, pp. 309, 395.

DEVELOPMENT OF NEW EXPERIMENTS AND IMPROVEMENT OF EXISTING EXPERIMENTS.

The next section of my address deals with specific attempts to improve upon the regular apparatus used in laboratories, and to introduce fresh experiments. In this work I must not forget to mention that in the development of the following pieces of apparatus it is only through the efforts of my keen and loyal staff at East London College that some of my ideas have been brought to fruition, and in such development work we have been assisted also by certain senior students. Further, I ought to acknowledge the value of the work done by the College Instrument Workshop staff. These examples are shown, because it is thought possible that some of the ideas incorporated in them might be applied in various devices used by members of this Section.

Successes.

(*a*) Force on a current-conveying conductor in a magnetic field.

(*b*) Relation of magnetic pull to flux density across a gap.

(*c*) Delineation of hysteresis loops for various magnetic materials by optical means.

(*d*) Relation of rotating hysteresis and flux density.

(*e*) Theoretical electrostatic field distribution in the dielectric of a single-core and a 3-core cable.

(*f*) Electrostatic field around an insulator.

(*g*) Rapid determination of electrical resistivity and temperature-coefficient of various materials.

(*h*) Optical efficiency of cinema projector from arc to screen.

Apparatus illustrating (*a*), (*b*), (*c*), (*e*), (*f*), and (*g*), were shown on the occasion of the delivery of this Address, and I am much indebted to Messrs. P. F. Soper, V. A. Hughes, C. H. W. Clark, and L. S. Piggott, for enthusiastic help in arranging these experiments so that they were shown in operation. Short notes on five of these follow.

(*a*) *Force on a current-conveying conductor in a magnetic field.*—The leading ideas underlying the design of this apparatus were: (i) To weigh directly the pull on the conductor itself. (ii) To arrange that the forces to be dealt with shall be of considerable magnitude, say of the order of grammes (not milligrammes). (iii) That the apparatus should be robust, and yet sensitive.

The apparatus in its present form (see Fig. 1) was designed about 1905 by my first lecturer, Mr. L. Murphy, after a general discussion with me as to the most hopeful lines along which to proceed. It has been entirely successful in its object. Further developments suggest themselves, such as arranging the apparatus to measure the force on a conductor in a slot, the force on the teeth of the slot, and the combined force on the conductor and the teeth.

(*b*) *Relation of magnetic pull to flux density across a gap.*—It had early been realized, from work which I had done for Sir Ambrose Fleming about 1897, that it was a difficult matter to devise a robust piece of apparatus for this purpose. The results obtained were always erratic, and generally the pull was of the order of 30 per cent too high, especially at low flux densities.

The primary idea embodied in the present apparatus was to reduce to a minimum the number of possible varying magnetic contacts; the number has been reduced to one only, this being the contact between the two faces where the force is to be measured. This was rendered possible by the use of a magnetic flexible joint which, while having constant reluctance, is yet sufficiently flexible to act as the equivalent of the knife-edge in a balance. The final form of this apparatus,* which is shown in Fig. 2, is the outcome of some long and patient work by Mr. C. R. Stoner, a member of my teaching staff, with the assistance at one time of Mr. Vardy.

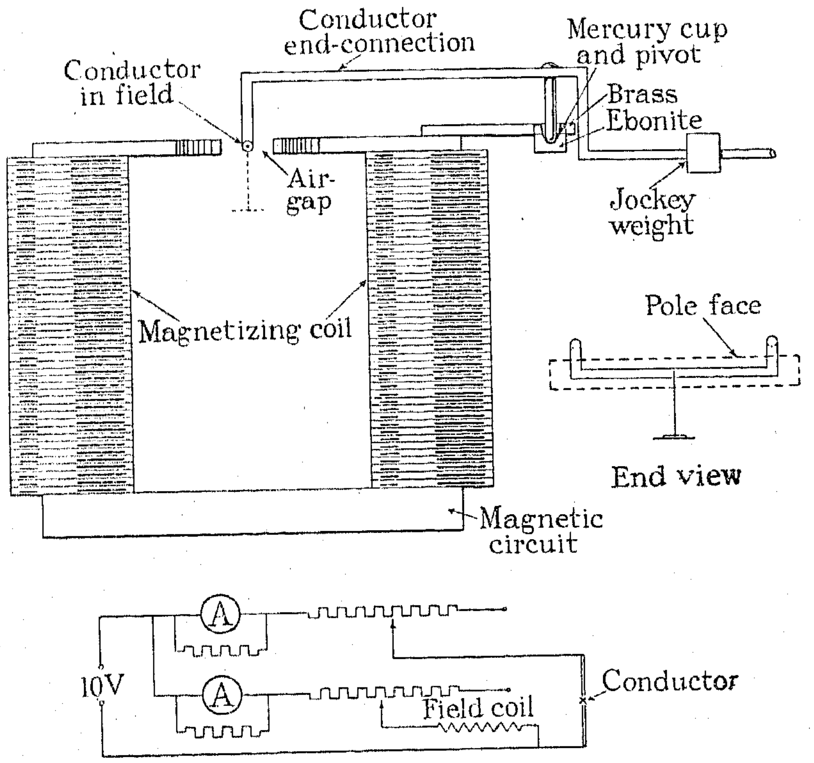

FIG. 1.—Apparatus for measuring force on current-conveying conductor in magnetic field.

(*c*) *Delineation of hysteresis loops for various magnetic materials by optical means.*—The primary idea embodied in this apparatus is not novel, but it has been applied so as to give more nearly quantitative results than in earlier instruments. The object is to give a beam of light reflected from a mirror a horizontal angular motion proportional to H, whilst its vertical angular tilt is made proportional to B for the magnetic specimen under test. The chief difficulty is to obtain a vertically tilting field proportional to B. As the vertical magnet attached to the back of the mirror must necessarily be free to tilt in an air-gap, the problem is to reduce the reluctance of this gap to a value small in comparison with that of the specimen under test. This is brought about by terminating the ends of two long thin magnetic specimens by mumetal pole-pieces of large area separated by as

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* *Proceedings of the Physical Society*, 1935, vol. 47, p. 186.

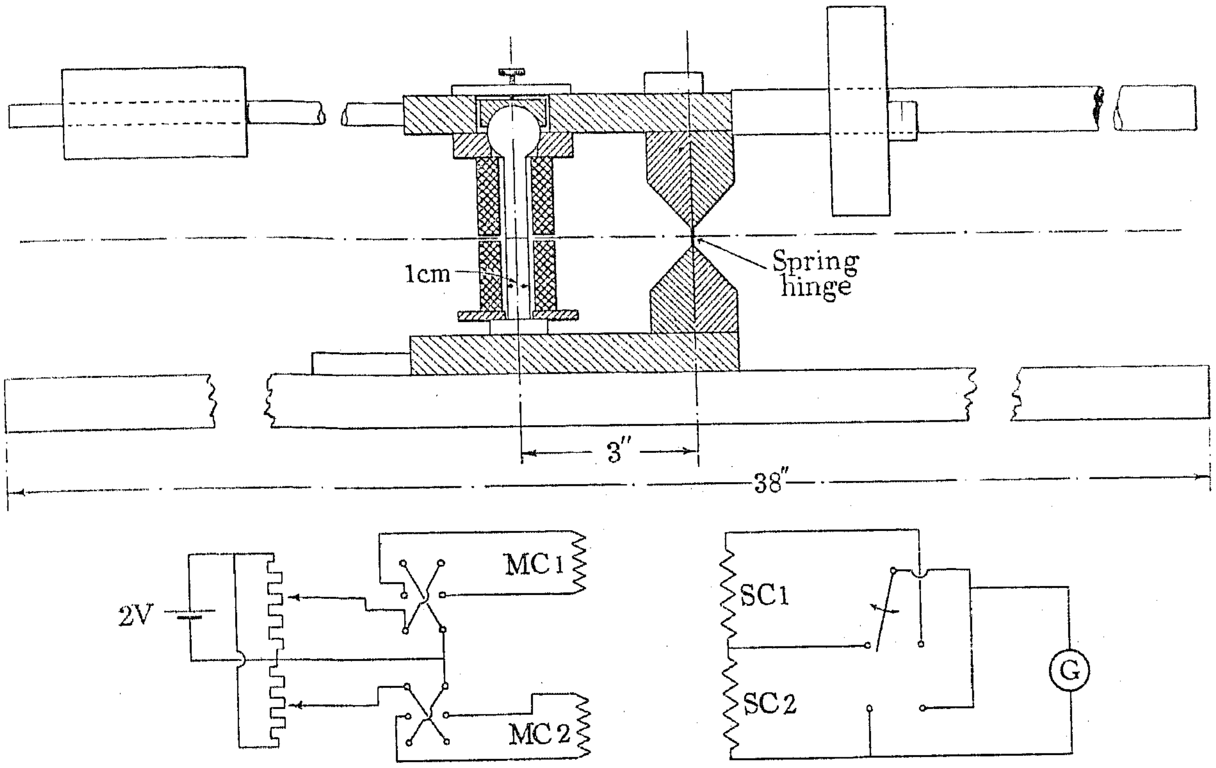

FIG. 2.—Apparatus for determining relation of magnetic pull to flux density across a gap.

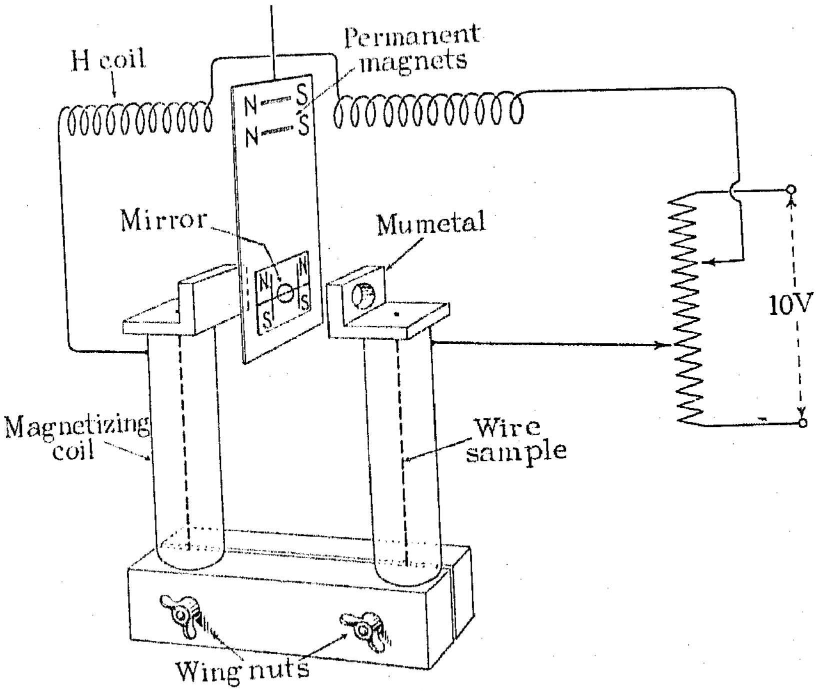

FIG. 3.—Apparatus for delineation of hysteresis loops by optical means.

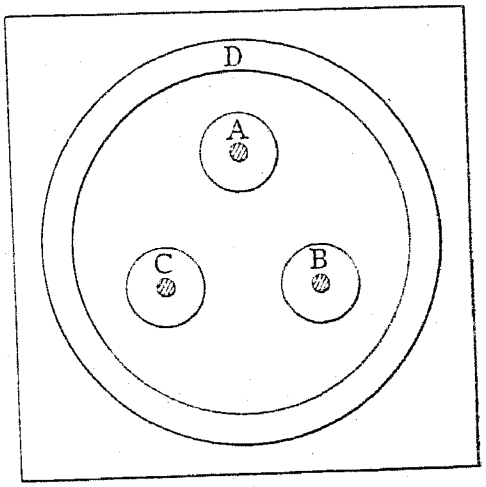

FIG. 4.—Apparatus for investigating theoretic electrostatic field distribution in dielectric of a single-core and a 3-core cable.

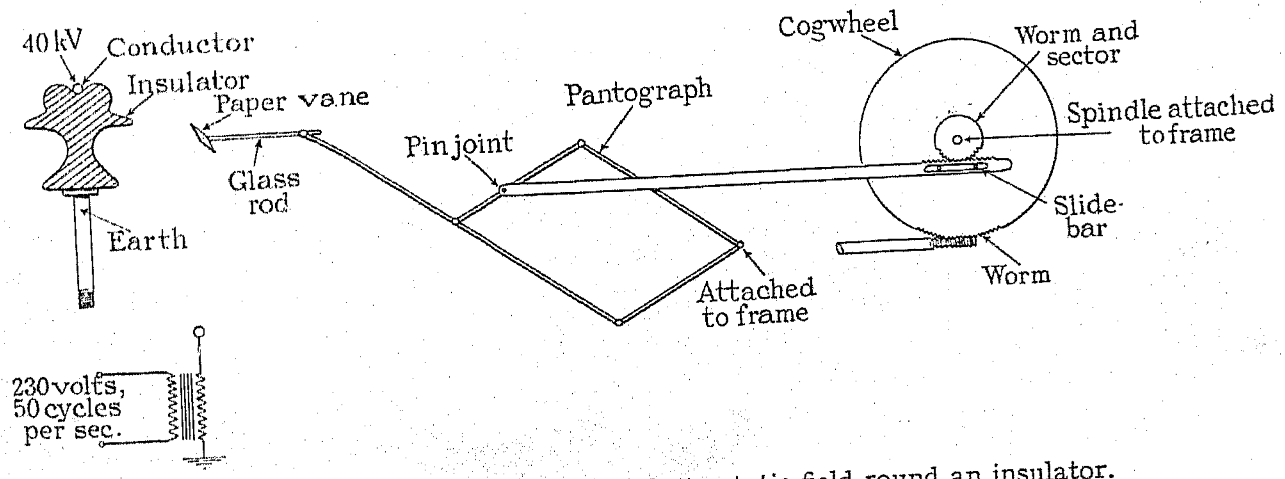

FIG. 5.—Apparatus for mapping electrostatic field round an insulator.

short an air-gap as is consistent with the free movement of the tilting magnet. The two wires under test are about 18 in. long and of about No. 20 S.W.G.

When highly permeable magnetic materials such as mumetal have to be tested, the whole apparatus is arranged in the centre of a tall vertical solenoid carrying a current of such a value that the vertical component of the earth's field is exactly neutralized. This apparatus is illustrated in Fig. 3, and the credit for its development is principally due to Messrs. H. Wright and H. W. Kay.

(*e*) *Theoretical electrostatic field distribution in the dielectric of a single-core and a* 3-*core cable.*—A model of perhaps twice to four times full size of a section of the cable is made by cutting out in sheet copper three discs—A, B, and C—having the sections of the cores, and a ring D of the section of the sheath outside (see Fig. 4). These are then sweated into intimate contact with a thin sheet of some high-resistivity material such as eureka. A direct current of 100 amperes is led in at A from a 4-volt battery and taken out at B and C in any desired proportions, the adjustment being by means of two carbon rheostats, one in the B circuit and the other in the C circuit. Then the equipotential lines can be plotted on the eureka sheet by means of a simple zero indicating galvanometer and a pair of rods terminated with eureka spikes. These lines of equipotential are distributed in exactly the same way as they would be in a cable, provided the dielectric acted as a perfectly uniform one in which there were no air pockets. This is a simple way of bringing home the theoretical distribution, and the modifications which occur in practice are more easily understood by the student who has done this simple experiment previously.

(*f*) *Electrostatic field around an insulator.*—The diagram of this apparatus (Fig. 5) is practically self-explanatory. The pantograph arrangement of holding an insulated paper needle so that it can be placed anywhere near a pin insulator is arranged so that a shadow of the insulator is produced by means of a Pointolite lamp placed about 3 ft. from the insulator, on a screen placed 3 ft. the other side of the insulator. The result is that the insulator stands out as a black shadow, and the shadow of the paper needle indicates the direction of the line of electrostatic force at the point at which it is placed. In this way the electrostatic field surrounding such an insulator can be marked out. A voltage of about 40 000 to 45 000 volts is suitable, and this can be supplied from quite a compact little transformer. The successful development of this apparatus is due to Mr. S. E. Goodall, working under the general direction of Mr. W. J. John.

Failure.

Determination of the electrochemical equivalent of copper.—The leading idea was the use of a copper hydrometer-shaped electrode floating in an electrolyte of copper-sulphate solution.

Difficulties cropped up owing to change of density of the electrolyte around the cathode and anode, and there were also difficulties in leading the current out from the floating cathode without disturbing its balance. It requires much more work to produce a practical article, but I have by no means abandoned hope of success.

Suggestions.

It is obvious that every college and technical institute should not follow the same rigid course in electrical engineering laboratory practice. I feel, however, that it may be helpful to place on record the method which I have found by many years of experience to produce good results. It has to be remembered that the students with whom I have to work are practically only those who have passed the University of London Intermediate Engineering Examination or its equivalent, and so my remarks are necessarily of limited application. At the same time they may suggest to others possible improvements.

Up to the present no attempt has been made at East London College to subdivide electrical engineers into the so-called "light" and "heavy" groups. It is of course fully realized that, in deciding against such subdivision, the training in each particular section of the subject cannot be taken so far, and on this account it is open to criticism. On the other hand, do we not know of many cases where a "heavy" trained electrical engineer finds that he has to take up "light" electrical engineering, and vice versa? Not only so, but we all know of more than one instance where so-called "light" engineering has become heavy engineering. I feel, therefore, that there is certainly room for such a scheme.

College Training of Selected Post-Graduate Students in Research Methods.

After completing the course for the B.Sc.(Eng.) degree, the majority of the students enter some electrical engineering manufacturing firm to obtain a practical training. For those, however, who desire to obtain an insight into the methods of research the course at East London College has been carefully planned. An outline of the general scheme will now be given.

The prospective research worker is first asked to suggest any possible lines of research which he would like to undertake. The professor then discusses the pros and cons (occasionally suggesting some lines of his own) from various points of view, firstly with reference to the equipment and personnel of the department, secondly with regard to the cost of the researches, and thirdly with regard to the possibility of achieving something of value within one year.

Having decided upon a suitable subject, the student is advised to improve his knowledge of technical German so as to be able to read original papers in this language, and if possible to read some advanced physics and mathematics. The regular use of *Science Abstracts* is essential, and the following method has been found practicable. The professor or lecturer directing the research goes carefully through each issue of Sections A and B month by month as they come out, and marks the number of each abstract bearing on any piece of work going on in the laboratory, or which it is proposed to undertake in the near future. The research worker then takes the numbers referring to his own work, and cuts the abstract out of either of two copies, depending on whether it appears on a left-hand or a right-hand page. In this way a complete cutting can be obtained of every abstract. The worker then mounts each of his abstracts on a card, and files it in a research card-index. The card index grows month by month, and when the research worker comes to write up the research this index is invaluable. Also, if the research work has to be handed over to another worker, the card index is most helpful in passing on recent knowledge. Of course, the aim is to train the research worker to find for himself all these abstracts bearing on his work.

As time goes on, the student discovers that he can apply his knowledge of electrical engineering to solve new problems. Up to the B.Sc. degree examination he has been so fully occupied with the attempt to cover a wide field that the knowledge obtained has hardly had time to become a part of the student's mental equipment, and the opportunity that a further year at college offers, if rightly used, can produce a wonderful development of true confidence in the power to use his knowledge. Further, this year should provide a definite training in developing those qualities which will lay the foundation of the art of keeping abreast of the new developments of his subject.

Finally, it is essential for the student to avoid too diffuse work. There must be a keen desire to round off the particular piece of research undertaken—in other words, to develop the habit of completing a piece of work—and then to put it into such a form that it may be of value to the profession of which he is a member, though as yet a very junior one.

He thus endeavours to fulfil Faraday's notable dictum—" WORK, FINISH, PUBLISH."

PROCEEDINGS OF THE INSTITUTION.

873RD ORDINARY MEETING, 8TH NOVEMBER, 1934.

Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 25th October, 1934, were taken as read, and were confirmed and signed.

Messrs. E. S. Ritter and W. L. Wreford were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, it was reported that the members whose names appeared on the lists (see vol. 75, page 830) had been duly elected and transferred.

The President announced that, during the month of October, 66 donations and subscriptions to the Benevolent Fund had been received, amounting to £72. A vote of thanks was accorded to the donors.

A paper by Messrs. A. S. Valentine, Associate Member, and E. M. Bergstrom, entitled " Hydro-Electric Development in Great Britain, with special reference to the Works of the Grampian Electricity Supply Co." (see page 125), was read and discussed.

The meeting terminated at 7.50 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

874TH ORDINARY MEETING, 22ND NOVEMBER, 1934.

Mr. H. T. Young, Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 8th November, 1934, were taken as read and were confirmed and signed.

A paper by Messrs. C. Wallace Saunders, Associate Member, H. W. Wilson, Associate Member, and R. G. Jakeman, D.Sc., Member, entitled " Generation, Distribution, and Use of Electricity on Board Ship " (see page 241), was read and discussed.

The meeting terminated at 7.55 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

875TH ORDINARY MEETING, 6TH DECEMBER, 1934.

Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 22nd November, 1934, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that, during the month of November, 32 donations and subscriptions to the Benevolent Fund had been received, amounting to £48. A vote of thanks was accorded to the donors.

A paper by Messrs. R. Grierson, Member, and D. Betts, Associate Member, entitled " The Electrical Warming of and the Supply of Hot Water and Conditioned Air to Large Buildings " was read and discussed.

The meeting terminated at 8 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

INSTITUTION NOTES.

The Secretary.

At the Annual Dinner of the Institution, held at Grosvenor House on the 7th February, the President announced that the President of the French Republic had conferred on Mr. P. F. Rowell, Secretary of the Institution, the distinction of Officer of the Legion of Honour. The ribbon and badge were presented to Mr. Rowell at the Dinner by Monsieur J. Grosselin, Director of the Société Française des Électriciens.

Graduateship Examination Results: November, 1934.

SUPPLEMENTARY LIST.*

Passed.†

Agrawala, H. L. (India).
Alagaratnam, K. V. (Ceylon).
Banks, A. (South Africa).
Burns, I. G. (New Zealand).
Chellam, S. V. (India).
Chunilal, V. (India).
Dave, N. M. (India).
D'Souza, A. (India).
Fowlds, R. H. (South Africa).
Ghosh, J. (India).
Gulati, B. J. (India).
Handyside, J. S. (New Zealand).
Haslett, K. (New Zealand).
Hillary, H. W. (South Africa).
Iyengar, M. V. A. (India).
Jesuratnam, S. (India).
Jewsbury, E. (New South Wales).
Laing, G. G. (South Africa).
Lewis, K. (South Africa).
McIntyre, C. (New Zealand).
Mayall, R. E. (South Africa).
Mead, W. E. (New Zealand).
Murty, K. R. K. (India).
Nair, N. A. K. (F.M.S.)
Nair, V. K. R. (India).
Nicol, S. M. (New Zealand).
Nield, C. F. (Egypt).
Rajagopalan, K. R. (India).
Rangachari, T. S. (India).
Read, G. S. J. (New Zealand).
Redpath, F. R. (New Zealand).
Sanderson, K. C. (New Zealand).
Shukla, R. B. (India).
Sinha, S. P. (India).
Smith, H. (Zanzibar).
Sohoni, K. V. (India).
Tudhope, G. W. (South Africa).

Passed PART I only.

Akhurst, F. K. (New Zealand).
Albuquerque, A. M. (India).
Andrew, W. M. (South Africa).
Bhatt, I. C. (India).
Bryce, J. F. (New Zealand).
Chopra, H. L. (India).
Daruvala, S. A. (India).
Desai, B. M. (India).
Desai, S. F. (India).
Dhondy, R. F. (India).
Elavia, B. G. (India).
Engineer, M. F. (India).
Glendenning, J. A. (India).
Hands, R. C. (New Zealand).
Kagalwala, V. R. (India).
Khanna, M. L. (India).
Lucas, W. H. L. (New South Wales).
Mistry, B. M. (India).
Mital, W. R. (India).
Pillai, K. K. (F.M.S.)
Read, E. E. (New Zealand).
Surveyor, B. N. (India).
Wilding, A. J. F. (South Africa).

Passed PART II only.

Black, R. F. (New Zealand).
Dantu, K. M. (India).
Dickens, T. A. J. (New Zealand).
Karanjia, N. M. (India).
Narayana Rao, T. (India).
Ohlssen, C. O. W. (South Africa).
Rasmussen, W. N. (New Zealand).
Selvanayagam, S. (Ceylon).
Smith, T. C. (New Zealand).
Thomas, E. (H.M.S. Medway).

"World Survey."

A new monthly journal, entitled "World Survey" will commence publication in April under the auspices of the World Power Conference. Its purpose will be to publish information on the production of power and on fuel (especially the economic aspects), and to collect basic data.

It will contain an International Power and Fuel Bibliography covering all outstanding publications on power and fuel, and the Power and Fuel Bulletin of the British National Committee will be merged in this Bibliography.

The subscription rate will be £2 per annum. Full particulars and a copy of the prospectus can be obtained on application to the British National Committee, World Power Conference, 36 Kingsway, London, W.C.2.

Proceedings of the Wireless Section.

116TH MEETING OF THE WIRELESS SECTION, 7TH NOVEMBER, 1934.

Mr. G. Shearing, O.B.E., B.Sc., Past-Chairman, took the chair at 6 p.m.

The minutes of the meeting held on the 2nd May, 1934, were taken as read and were confirmed and signed.

Mr. Shearing announced the Council's award of Premiums (see vol. 74, page 603) for papers read before the Section during the session 1933–34. He then vacated the chair, which was taken by Mr. S. R. Mullard, M.B.E., Chairman.

A vote of thanks to Mr. Shearing for his services as Chairman during the session 1933–34, proposed by Mr. F. S. Barton and seconded by Dr. W. F. Rawlinson, was carried with acclamation.

Mr. S. R. Mullard, Chairman of the Section, then delivered his Inaugural Address (see page 10).

A vote of thanks to the Chairman for his Address was proposed by Mr. Shearing and carried with acclamation.

The meeting terminated at 7.5 p.m.

117TH MEETING OF THE WIRELESS SECTION, 5TH DECEMBER, 1934.

Mr. S. R. Mullard, M.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 7th November, 1934, were taken as read and were confirmed and signed.

A paper by Mr. R. H. Barfield, M.Sc.(Eng.), Associate

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* See page 239.

† This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Member, entitled "Some Principles Underlying the Design of Spaced-Aerial Direction-Finders," was read and discussed.

The meeting terminated at 7.56 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

118TH MEETING OF THE WIRELESS SECTION, 2ND JANUARY, 1935.

Mr. S. R. Mullard, M.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 5th December, 1934, were taken as read and were confirmed and signed.

A paper by Messrs. A. B. Wood, D.Sc., F. D. Smith, D.Sc., Associate Member, and J. A. McGeachy, B.Sc., entitled "A Magnetostriction Echo Depth Recorder" was read and discussed. A demonstration was afterwards given,

The meeting terminated at 8.2 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

Elections and Transfers.

At the Ordinary Meeting of the Institution held on the 24th January, 1935, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

Bellaschi, Peter Louis, M.Sc.
Bird, Jack William G.
Bishop, Kenneth Falle.
Brierley, James, B.A.
Callow, Ernest Walter.
Clemence, Edward, B.Sc.
Cocks, Adrian Harry W. J., B.A.
Cooper, Mark Cyril.
Cox, Cecil Louis.
Crawshaw, Bernard Slater, B.Sc.(Eng.).
Dean, Ralph Hubert, B.Sc. Tech.
Dixon, Adam Gordon.
Dixon, Bernard.
Ewbank, Henry Vandyke, Lieut., R. Signals.
Ferris, Gilbert Thomas.
Finkelstein, Izak-Ignacy, Dipl. Ing.
Garwood, Godfrey Thos., B.Sc.(Eng.).
Gracie, Andrew John A., B.Sc.
Grant, Ralph Marshall W., B.Sc.
Gueilikman, Michael.
Harding, Harry Arthur.
Harris, Hubert David.
Hickernell, Latimer Farrington.
Hippisley, Edward Townsend, B.A.
Hobbs, Harold.
Irving, David Blair, B.Sc.
Jackson, Thomas Anthony.
Leach, Granville William.
Ledsom, Alexander, M.Eng.
Long, Ernest.
McHaffie, Hugh Gordon, B.Sc.
Mair, Philip Beveridge, B.A.
Mathiesen, Hugh Matthias.
Metelerkamp, Aubrey Rawstorne.
Mitchell, Henry Thomas.
Nettleship, Thomas Geoffrey P., B.Sc.(Eng.).
Oldroyd, George Herbert.
Pollock, Henry Latimer.
Randle, George Hurst, B.A.
Reynolds, John Alfred E., B.A., B.A.I.
Rudkin, John Bernhard.
Scott, William Carlisle.
Shettle, William Croasdill.
Taggart, James Ewart.
Wallace, John, B.Sc.
White, William Uttermare, M.C.
Whitmore, Geoffrey.
Wilton, Donald Victor.
Wright, Alexander, B.Sc.

Associates.

Barnes, John.
Beadman, Cyril Benjamin H.
Brown, Frederick Oswald.
Clark, Charles Walter.
Comber, Charles Thomas T.
Garnett, Harry Seys.
Homer, Theodore Graham.
Howles, Leonard.
Hutton, William Stanley.
Leathwood, Cyril William.
McLean, George Clark.
Morrison, George Wright.
Parker, William Clifford.
Payne, Robert Gwin.
Pluck, Arthur Durell.
Salisbury, Ralph Frederick.
Scholes, Terry Howroyd.
Small, Andrew James D., B.Sc.
Steel, Charles Henry J.
Sutcliffe, Herbert Henry.
Thomson, Charles John.
Wrightam, Leonard.

Graduates.

Allan, Charles Lewis C., B.A.
Amos, Wilfred Jack.
Andrews, William Hannaford.
Anketell, Cecil Augustus R.
Ashworth, Harry Clifford.
Bacon, Charles Cecil.
Baxter, Edward Wakeford.
Bell, William Wallace.
Bharucha, Burjorji Dinshawji.
Bhattacharyya, Pradyot Kumar, B.Sc.
Bhojwani, Chiman Kundanmal, B.Sc.Tech.
Bibby, Herbert Frederick, B.Sc.Tech.
Blunt, Arthur, B.Sc.(Eng.).
Blythe, Cecil.
Blythe, Matthew Clark, Jun.
Bradley, Basil Dermot, B.Sc.
Broadbent, Harold.
Brockelsby, Charles Fountain, B.Sc.
Brown, Robert Ross B., B.A., B.Sc.
Bulled, Stanley Boundy.
Callender, Marshall Wightman.
Campin, Ralph Henry.
Cavendish, Geoffrey Manners.
Challands, Arthur Cecil, B.Sc.
Chandler, Cyril William.
Clarke, Kenneth John.
Cockram, Reginald William J.
Cook, Thomas Henry, B.Sc.(Eng.).
Copsey, Thomas.
Corson, Geoffrey Jameson.
Cover, William.
Coventry, Henry Brown.
Dance, Geoffrey.
Davies, David Gwyn, B.Sc. (Eng.).
Davies, Trevor John, B.Sc.
Davis, John James.
de Courcy, Frederick James, B.A., B.A.I.
Donnan, David.
Donnelly, George Matthew F.
Double, Ernest Walter W., B.Sc.(Eng.).
Druce, James Milton, B.A.
Dunn, Ralph Cyril.
Eaton, Edward Joseph, B.Sc.
Evans, Cyril James.
Falconar, John Oswald.
Ferrari, Andrea, Dott. Ing.
Finden, Harold Jack.
Fletcher, William John C., B.Sc.(Eng.).
Floyd, Cyril Farvis, B.A.
Friel, Geoffrey Manning S., B.A., B.A.I.
Garry, Francis Keith, B.E.
Gomm, William Henry C., B.Sc.(Eng.).
Gordon-Smith, George William.
Gregory, Henry James.
Halstead, Frederic John.
Hamer, Sidney Acton, B.Sc.Tech.
Heard, Sydney Richard, B.Sc.
Hensler, Eric, B.Sc.(Eng.).
Henson, Clarence William.
Hill, Frederick Robert.
Howlett, Francis Charles.
Ingall, Howard Kenneth, B.A.
Jarman, Leslie Cecil.
Johnson, Harold Bell, B.Sc.
Jones, Frederick Charles, B.Sc.(Eng.).

Graduates—continued.

Kaplan, Emanuel.
Kerr, Henry, B.Sc.
Kininmonth, Ronald.
Knox, John, B.Sc.
Lacy-Hulbert, Cyril, M.A.
Lawrence, William Minett.
Lawlor, James Butler S.
Lewis, Ivan Jack W.
Livesey, Joseph Bleasedale.
Mabe, William Stanley, B.Sc.
Macdonald, Stewart James, B.Sc.
McIlhagger, David Sherwood, B.Sc.
McIntosh, James Colin, M.Sc.
McKenna, Angus Threlfall, B.Eng.
Mather, Fred.
Markland, John Downes.
Mason, Thomas Frederick.
Masters, Kenneth Lindley.
Meakin, Charles Wilfred.
Morris, Joseph Ernest.
Narayan, Shiva, B.Sc.Tech.
Neate, Alan David.
Nevrekar, Madhav Laxman, B.Sc.Tech.
Oubridge, George Dinsdale.
Perkins, Frederick Cornelius, B.Sc.(Eng.).
Peters, Arthur Paul L.
Plant, Kenneth.
Priestland, Arthur Douglas.
Priestley, Henry Thomas, B.E.
Pursey, Ronald Thomas, B.Sc.(Eng.).
Putham, Adolph Rupert, B.E.E.
Ralphs, Victor.
Rao, Kundaje Sitarama.
Rawnsley, Cecil Frederick.
Rees, John Glyn, B.Sc.
Ridding, Arthur.
Roebuck, John Spencer, B.Sc.
Rudd, Harold Crompton.
Sageman, Walter John.
Sambasiviah, Gurikar, B.Sc.Tech.
Sanderson, John.
Scott, James, B.Sc.
Seaman, Eric Charles H., B.Sc.(Eng.).
Shallcross, John Eric.
Sharpe, Leslie William.
Shaw, Mansergh.
Shinghal, Darshan Dayal, B.Sc.
Shiva, Abol Qassem, B.Sc.
Shivdasani, Bhagwan Rupchand.
Smith, Edwin Leslie, B.Sc.
Smith, Kenneth Ashbrooke, B.Sc.
Spencer, Arthur Morrell, B.E.
Staddon, Edward Charles.
Stewart, John, M.A., B.Sc.
Sujan, Vishindas Bagomal.
Taha, Ahmed Adham.
Thomas, Harry Everett S., B.Sc.(Eng.).
Thorns, Geoffrey Heaton.
Towns, Douglas Henry, B.Sc.
Townshend, Alfred George, B.E.
Turner, Leonard.
Vandersyde, Francis Eric.
Varma, Bhagwan Das.
Walwyn, George Harold, B.Sc.
Watson, Norman, B.Sc.
Webber, Cyril Benjamin.
Wey, Raymond John.
Willoughby, Eric Osborn, B.E.E., B.A.
Wilson, Thomas Edward.
Young, Thomas.

Students.

Adams, Arthur James C.
Adcock, Stanley Foster.
Aird, John.
Alagaratnam, Kurunathar Vallipuram.
Allison, Charles Thomas.
Allison, Jack Whitwell.
Allison, James.
Amanat, Nasirali.
Ames, Albert Kenneth.
Anscombe, Hedley Jesse E., B.Sc.
Armstrong, Gordon.
Arscott, Joseph William.
Bahns, Harold Watts.
Bailey, Desmond.
Bales, Robert Hyde.
Ball, Ronald.
Ballington, Basil.
Banerjee, Donald Nolini K.
Barker, Harry.
Barnett, Rainald Frank.
Bastin, Douglas James.
Bates, Eric.
Bazeley, William Kinghorn.

Students—continued.

Bauchop, Lindsay Haliday.
Bechervaise, Eric Walter.
Bell, William.
Bendall, Roland John.
Bentley, William Leslie.
Benzie, Athol Emslie.
Bhagut, Dara Dadabhoy.
Bhatt, Induprasad Chhotalal, B.Sc.(Eng.).
Bhatty, Mohammad Sharif.
Bhide, Gopal Ramchandra, B.Sc.(Eng.).
Bickley, Herbert Dunn.
Biggs, Frank William T.
Bimbrahw, Jot Ram.
Bishop, Dudley Oswald.
Bissmire, Henry George T.
Black, William David.
Bland, Sydney.
Booth, Eric Stuart.
Bostock, Edward Thomas.
Boutros, Kamel.
Bown, John Edwin.
Bradbury, Norman Haynes.
Brass, David Francis S.
Breton, Paul Anthony.
Briggs, Herbert Denis.
Brocklehurst, Norman.
Brooke, Ralph Crichton R.
Brown, Haydn.
Browning, Roy William.
Bullen, Harold Howe.
Burgess, Alfred Gibbon.
Burnand, Donald William.
Butt, Mohammad Shafee.
Bygate, Richard Anthony.
Caish, Frederick Charles.
Calmeyer, Reginald.
Callow, John Hiner.
Campling, John Norman.
Capelli, Marino Pompeo G.
Carmichael, Ian.
Carter, Russell Sydney.
Chapple, Frederick John.
Chatterjee, Baidya Nath.
Chatton, Linton Thomas.
Cherrington, Kenneth Edward.
Chisholm, Wesley Perrin.
Chown, John Charles H.
Chu, Cheng-Yeh, B.Sc.
Clyde, Alexander Kenneth.
Cochrane, Thomas Richard H.
Cocks, Arthur Herbert.
Coffey, Albert William.
Cole, Gordon Leslie.
Collins, Walter Henry.
Comer, Murray Frederick.
Cox, Alan Henry.
Craft, Charles William.
Craig, Archibald Basil.
Cristiani, Abelardo.
Darnell, William Barrington.
Davies, Graham David.
Davies, John Herbert.
Davis, John.
Dennis, Philip Vincent.
Desai, Bhimbhai Manibhai, B.Sc.(Eng.).
De Villiers, Michael Arend N.
Dev, Promode Kusum.
Dobson, George Denis.
Doel, Ralph Francis.
Dowman, John Allen.
Drabble, Colin.
Drake, Bernard.
Duckett, Gerald Clifford.
Dunn, Arthur Dennis.
Dunne, Victor Conway.
Duttroy, Birendra Sanker.
Eades, David John.
Eades, Peter Frederick.
Edwards, Ivan George.
Elder, John Alexander.
Ellis, Eric.
Ellis, John Edward.
Esson, George.
Etheridge, Wallace Frederick C.
Evans, Douglas Dyfed.
Evans, Edward Neal.
Evans, John Dudley.
Everett, Kenneth Edward.
Fair, James Benjamin.
Farmery, William.
Fattal, Ezra E.
Ferguson, Oswald.
Fitzgerald, Jack George.
Flannery, Sidney Thomas.
Forte, Wilson Gordon M.
Foster, Norman Hylton.
Fowler, Charles Harold.
Francis, George Charles.
Friedberg, Eric.
Gabaldo, Italo.
Garner, Gerald Bernard.
Garrett, Maurice Arthur.
Gatter, Percy William.
Gaul, Richard John.
Gautam, Gokal Chand.
Geoghegan, Joseph Francis.
Ghate, Balkrishna Gopal.
Gibson, Alan Barraclough.
Goligher, Derek Garvin.
Goodwin, Richard Henry.
Gosling, Leonard Owen, B.A.
Graham, Joseph William.
Grais, Hanna, M.A.
Grant, Francis Cullen.

Students—continued.

Grant, William.
Gray, John Alwyn.
Grayson, Harry, B.Sc.Tech.
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Mulholland, Edward Bernard.
Mulla, Dadi Sorabji.
Muttiah, Sinnathamby Eliathamby.
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Students—continued.

Napier, Colin William S.
Narayanarao, S. N., M.Sc.
Nasif, Mohammed Abdel L.
Neill, Victor Alan.
Nicholson, Henry.
Ogle, William James.
Ohlssen, Christian Olaf W.
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Page, Albert William.
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Pleass, Brian John.
Points, Phillip Thomas.
Preist, Donald Henry.
Preston, Stuart Frederick.
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Saner, John.
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Sherwood, Wynne Maxwell.
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Warren, John Henry.
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Woodget, Thomas Silas.
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Hodges, Charles Culmer.
Illingworth, Robert.
Kibblewhite, Curtis.
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Mackenzie, William Aloysius.
Mackersey, Colin Alleyne.
Miller, John Leonard, D.Eng., Ph.D.
Mittell, Brenchley Ernest G.
Percival, Alfred John.
Pillans, James Pritchard S.
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Rendle, Gerald Alfred, B.Sc.(Eng.).
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Unwin, Dudley James.
Villares, Guilherme Dumont.

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Prosad, Bhagwat, M.Sc., B.L.
Rao, Nyayapati Srinivas.
Suarez, Anthony Joseph.
Wells, Harold Charles.
Wilson, Herbert Walter.
Wood, James Adie B.

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Baldwin, Cecil Spence S.
Barns, Harold Ernest, B.Sc.(Eng.).
Bayles, John Wallis, B.Sc. (Eng.).
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French, David Charles.
Friedman, Moses Jacob.
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Halton, Geoffrey Herbert, B.Sc.
Harrison, Arthur Casswell.
Harthan, Edmund Pring.
Hayes, Kenneth Alan, B.Sc.(Eng.).
Hodges, Philip George L.
Jones, Harold Hosgood.
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Graduate to Associate Member—continued.

Marryat, John.
Mayer, Vernon.
Millard, Robert George.
Milne, Grant Raglan, B.Sc.
Oldfield, Norman, B.Sc. (Eng.).
Onley, Eric Thomas F., B.Sc.
Ottmann, Percival Algernon, B.Sc.(Eng.).
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Phillips, Frederick Philip, B.Sc.(Eng.).
Pilcher, Cecil Walter.
Pratt, William Thomas, B.Sc.(Eng.).
Pulling, Martin John L., B.A.
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Scott, Eric Ronald.
Singh, Saudagar, M.Sc.
Skipsey, Joseph Fendley, B.Sc.
Smith, Frank Jervis.
Smith, Ian Stewart, B.Sc.
Smith, Stanley.
Spencer, Alfred Nicholas, B.E.
Steel, Walter Scott, B.Sc.(Eng.).
Stockwell, Thomas.
Sturley, Kenneth Reginald, Ph.D., B.Sc.
Taunton, Robert Dixon.
Thompson, Eric Alexander H.
Thompson, William Stanley.
Tye, Edward.
Wauchope, George Andrew.
Whiteley, Austyn Leslie, B.Sc.
Widnall, Frank, B.Sc.(Eng.).
Wilde, Samuel Francis M., B.E.
Wilkinson, Alfred Bentham.
Wilkinson, Kenneth James R., B.Sc.
Wilson, Eric, M.Eng.

Student to Associate Member.

Emerson, John Christopher, B.Sc.
Everest, Guy Neil.
Morrell, Francis Oliver, B.Sc.
Randle, James, M.Eng.
Rendle, Harold Barton.
Roberts, John Henry B.Sc.(Eng.).

Student to Associate.

Hamp, George Alexander.

In addition, the following transfers have been effected by the Council:—

Student to Graduate.

Cuthbert, Robert.
Hoare, Eric Ronald, B.Sc.(Eng.).
Hubbard, Carlos Douglas, B.Sc.
Jones, Clifford, B.Sc.(Eng.).
Short, Philip, B.Sc.(Eng.).
Tee, James Victor, B.Sc.(Eng.).
Whyte, David Connacher.

Accessions to the Reference Library.

[NOTE.—The books cannot be purchased at the Institution; the names of the publishers and the prices are given only for the convenience of members; (*) denotes that the book is also in the Lending Library.]

ADDISON, H., *M.Sc.* A text book of applied hydraulics. 8vo. xii + 409 pp. (London: Chapman and Hall, Ltd., 1934.) 21*s*. (*)

AGGER, L. T. Alternating currents. 8vo. viii + 204 pp. (London: Macmillan and Co., Ltd., 1934.) 5*s*. (*)

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Amberton, R. The power factor booklet. 2nd ed. sm. 8vo. 82 pp. (London: The Electrical Apparatus Co., Ltd., 1934.) 2*s.* 6*d.*

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Bacon, J., *M.B.E.* Bacon's commercial engineering. sm. 8vo. 288 pp. (London: Construction and Contracts.) 6*s.* (*)

Barnard, R. M. Radio receiver measurements. sm. 8vo. xii + 116 pp. (London: Iliffe and Sons, Ltd.) 4*s.* 6*d.* (*)

Boury, A., and Touvy, A. M. L'allumage des moteurs à explosions par bobine d'induction. sm. 8vo. 274 pp. (Paris: Librairie J.-B. Baillière et Fils, 1934.) 38 *francs.*

Bridgman, P. W. The thermodynamics of electrical phenomena in metals. 8vo. vi + 200 pp. (New York: The Macmillan Company, 1934.) 16*s.* (*)

Britton, H. T. S., *D.Sc.* Conductrometric analysis: principles, technique, applications. 8vo. xi + 178 pp. (London: Chapman and Hall, Ltd., 1934.) 12*s.* 6*d.*

Broglie, L. de. L'électron magnétique. (Theorie de Didac.) 8vo. viii + 315 pp. (Paris: Hermann et Cie., 1934.) 100 *francs.*

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Chapple, H. J. B. Television for the amateur constructor. 2nd ed. 8vo. xxiii + 266 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1934.) 12*s.* 6*d.* (*)

Charnock, G. F. Mechanical technology: being a treatise on the materials and preparatory processes of the mechanical industries. 2nd ed., revised and enlarged by F. W. Partington. 8vo. xii+725 pp. (London: Constable and Co., Ltd., 1934.) 15*s.* (*)

Childs, W. H. J., *Ph.D.* Physical constants selected for students. sm. 8vo. viii + 77 pp. (London: Methuen and Co., Ltd., 1934.) 2*s.* 6*d.*

Clark, C. H. D., *M.Sc.* The electronic structure and properties of matter. 8vo. xxv + 374 pp. (London: Chapman and Hall, Ltd., 1934.) 21*s.* (*)

Clayton, A. E., *D.Sc.(Eng.).* Alternating currents. 8vo. viii + 334 pp. (London: Longmans, Green and Co., 1934.) 10*s.* 6*d.* (*)

Cole, A. H., and Bigelow, K. W. A manual of thesis-writing for graduates and undergraduates. 8vo. vi + 48 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1934.) 4*s.*

Cotton, H., *M.B.E.*, *D.Sc.* Design of electrical machinery. la. 8vo. vi + 479 pp. (London: Oxford University Press, 1934.) 24*s.* (*)

Crowther, J. A., *M.A.*, *Sc.D.* Ions, electrons and ionizing radiations. 6th ed. 8vo. xi + 340 pp. (London: Edward Arnold and Co., 1934.) 12*s.* 6*d.* (*)

Davis, A. H., *D.Sc.* Modern acoustics. 8vo. xi+345 pp. (London: G. Bell and Sons, Ltd., 1934.) 26*s.* (*)

Dawes, C. L. A course of electrical engineering. vol. 2, Alternating currents. 3rd ed. 8vo. xxi + 705 pp. (New York, London: McGraw-Hill Publishing Co., Ltd., 1934.) 24*s.* (*)

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Book I, First year. viii + 160 pp. 5*s.* (*)
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vol. 3, Electricity and magnetism; transl. by L. A. Woodward. xiv + 685 pp. 25*s.* (*)
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Harris, H., *Ph.D.* Metallic arc welding. 8vo. viii + 199 pp. (London: Edward Arnold and Co., 1935.) 16*s.* (*)

Haslett, C., *C.B.E.* The electrical handbook for women. Edited for the Electrical Association for Women by C. Haslett. Foreword by Sir J. Snell. sm. 8vo. 416 pp. (London: Hodder and Stoughton, Ltd., 1934.) 5*s.* (*)

Henderson, J., *M.C.* Automatic protective gear for a.c. supply systems. sm. 8vo. xiv + 201 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1934.) 7*s.* 6*d.* (*)

Higbie, H. H. Lighting calculations. 8vo. xi + 503 pp. with 4 diagrams in pocket. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1934.) 37*s.* 6*d.* (*)

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Iliovici, A. Les coordonnées symétriques en électrotechnique. Etude théorique.—Application à l'étude des circuits polyphasés non equilibrés. sm. 8vo. 284 pp. (Paris: Librairie J. B. Baillière et Fils, 1934.) 35 *francs.*

Institution of Engineers, Australia. Recommended engineering drawing practice. 8vo. 128 pp. (Sydney: The Institution of Engineers, Australia, 1934.) 4*s.* 6*d.* *Australian currency.*

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Jeans, *Sir* J., *D.Sc.*, *LL.D.*, *F.R.S.* Through space and time. Based on the Royal Institution lectures, Christmas, 1933. 8vo. xiv + 224 pp. (Cambridge: University Press, 1934.) 8*s.* 6*d.* (*)

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Kesselring, F., *Dr.-Ing.* Elektrische Schaltgeräte und Regler. Bd. 1, Theoretische Grundlagen zur Berechnung der Schaltgeräte. sm. 8vo. 142 pp. (Berlin and Leipzig: Walter de Gruyter and Co., 1928.) *RM.* 1.80.

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Machinery's Handbook for machine shop and drawing office. 9th ed. sm. 8vo. 1592 pp. (New York, London: Machinery Publishing Co., Ltd., 1934.) 32*s.*

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—— Elements of loud speaker practice. sm. 8vo. viii + 160 pp. (London: Oxford University Press, 1935.) 5*s.* (*)

Mills, J. Signals and speech in electrical communication. 8vo. 281 pp. (New York: Harcourt, Brace and Co., 1934.) 12*s.* (*)

Needham, W. R. Some notes on mechanical design of high-speed salient-pole a.c. rotors. The Association of Engineering and Shipbuilding Draughtsmen. Session 1933–34. 8vo. 49 pp. (London: The Draughtsman Publishing Co., Ltd., 1934.) 2*s.*

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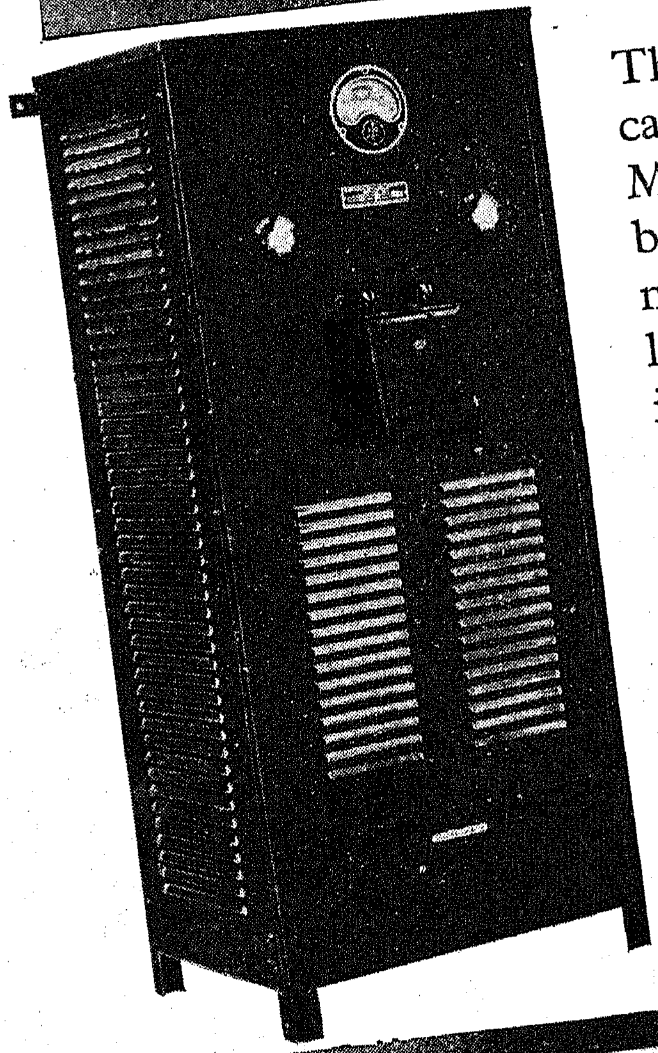
METAL RECTIFICATION *for* RELIABILITY



There are many commercial applications to which Westinghouse Metal Rectifiers may be put—battery charging, operation of magnetic valves and couplings, solenoids, lifts, electro-plating, spot-welding, inter-office telephones, etc.

The illustration shows a typical metal rectifier charging equipment supplied to the Birkenhead Corporation. We can supply a unit to meet any special needs.

May we send you our brochure D.P.11 "A.C. to D.C." or quote to your special requirements?

WESTINGHOUSE

METAL RECTIFIERS

WESTINGHOUSE BRAKE & SIGNAL CO., LTD.
82, York Road, King's Cross, London, N.1

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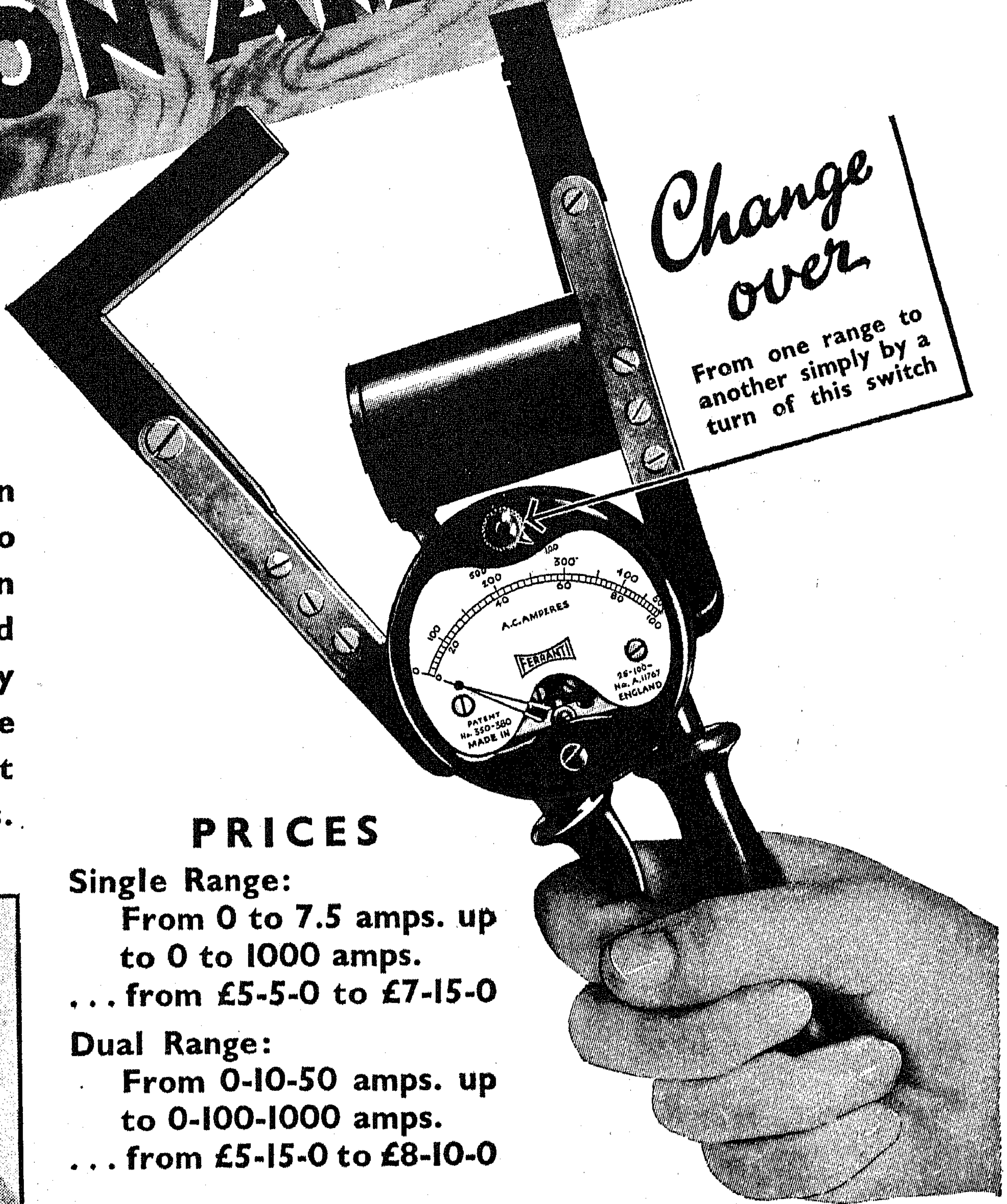
CLIP-ON AMMETER



Change over

From one range to another simply by a turn of this switch

The Ferranti Clip-on Ammeter enables you to measure the current in any circuit quickly and safely. It is merely clipped on to the cable and the instrument immediately registers.

PRICES

Single Range:
From 0 to 7.5 amps. up to 0 to 1000 amps.
. . . from £5-5-0 to £7-15-0

Dual Range:
From 0-10-50 amps. up to 0-100-1000 amps.
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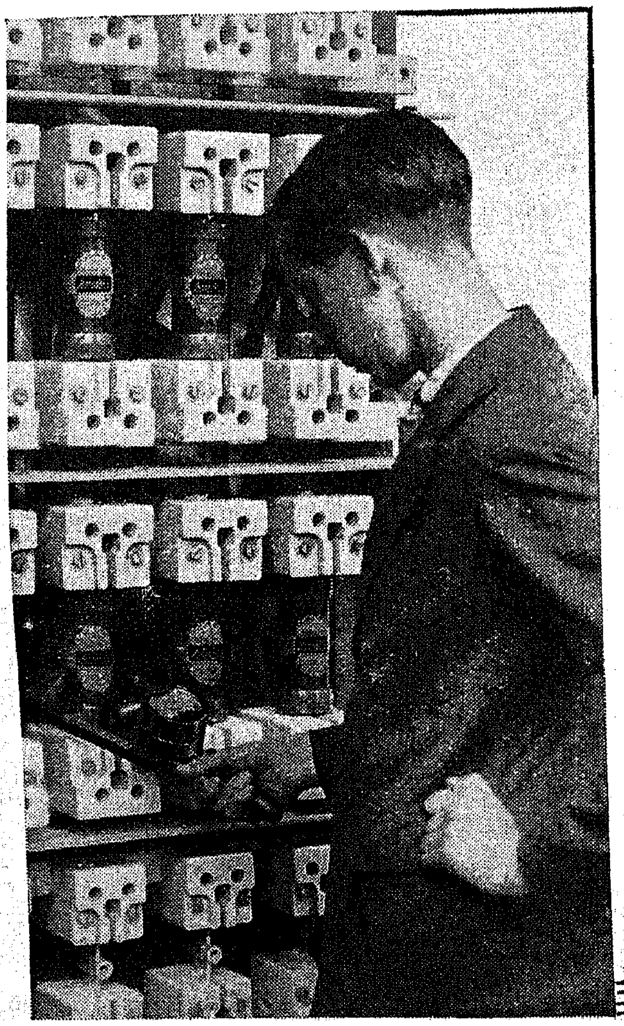

This instrument possesses several important features:—Two ranges in the one instrument. Self-aligning core with insulation covering. Insulating jaws take cables up to 2 inches. Good damping. Single-handed operation. Net weight: 2-lbs. 2-ozs.

Fullest particulars on application. *Write for List In.11.*

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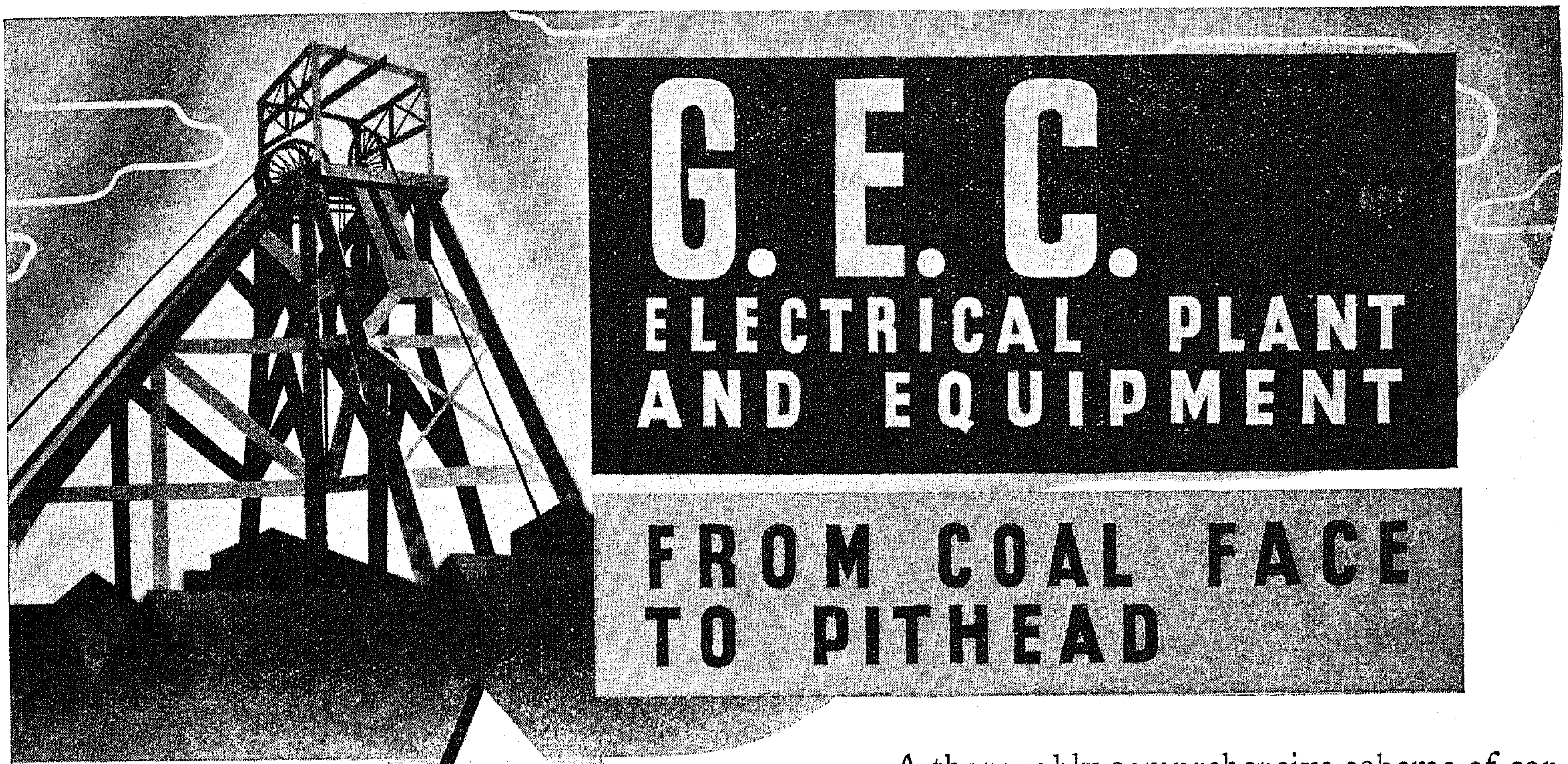

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FROM COAL FACE TO PITHEAD

A thoroughly comprehensive scheme of conversion to electrical power at Ryhope Colliery, Co. Durham, furnishes yet another example of the ability of the G.E.C. to undertake

COMPLETE ELECTRIFICATION SCHEMES OF ANY MAGNITUDE

Throughout this colliery from coal face to pithead G.E.C. electrical plant and equipment facilitates coal-getting in a most economical manner.

G.E.C. plant and equipment supplied for this undertaking includes :—

THREE
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Total capacity 8,000 h.p.

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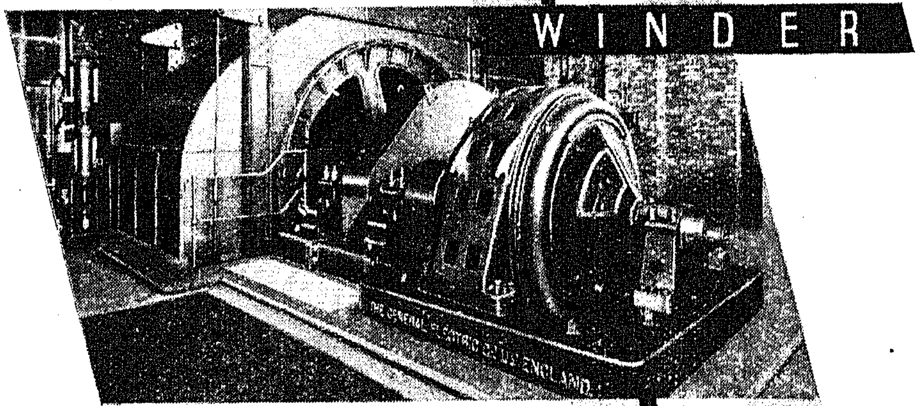
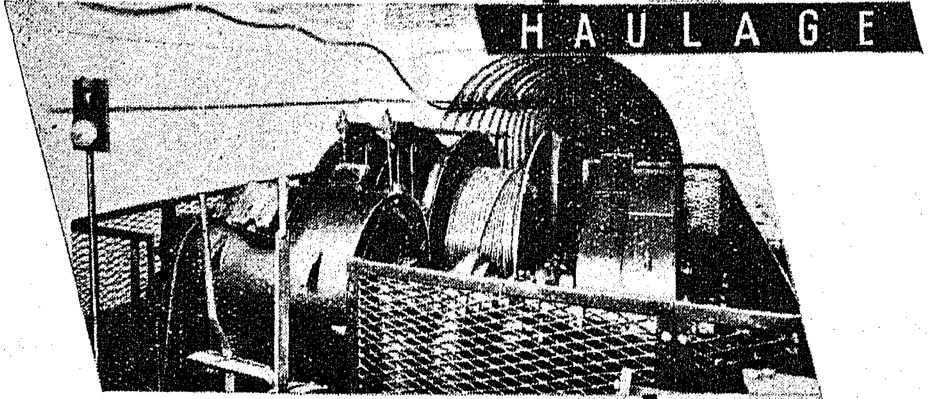
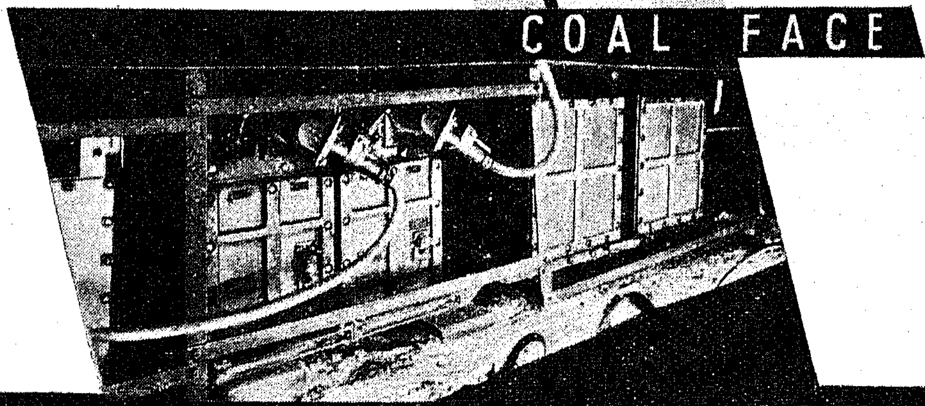


Underground haulage driven by 100 h.p. WITTON 3-phase motor



View at the coal face. G.E.C. gate end boxes in the Harvey Seam



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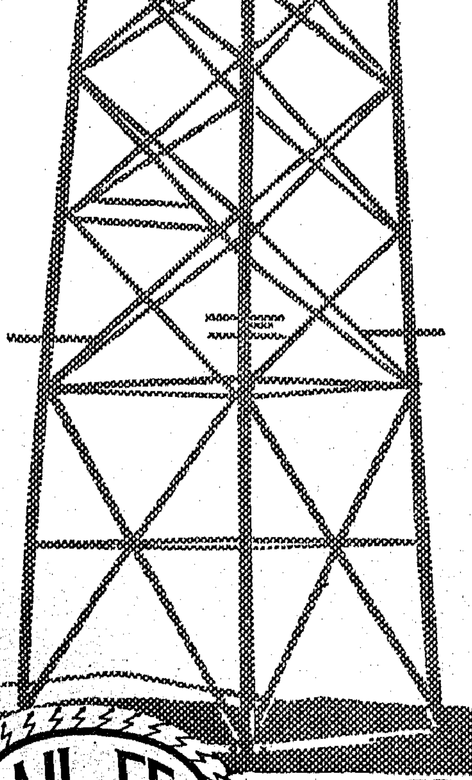

One Municipal Authority using over 9,200 "NIFE" cells has spent 45/- on spares and repairs in the last eight years.

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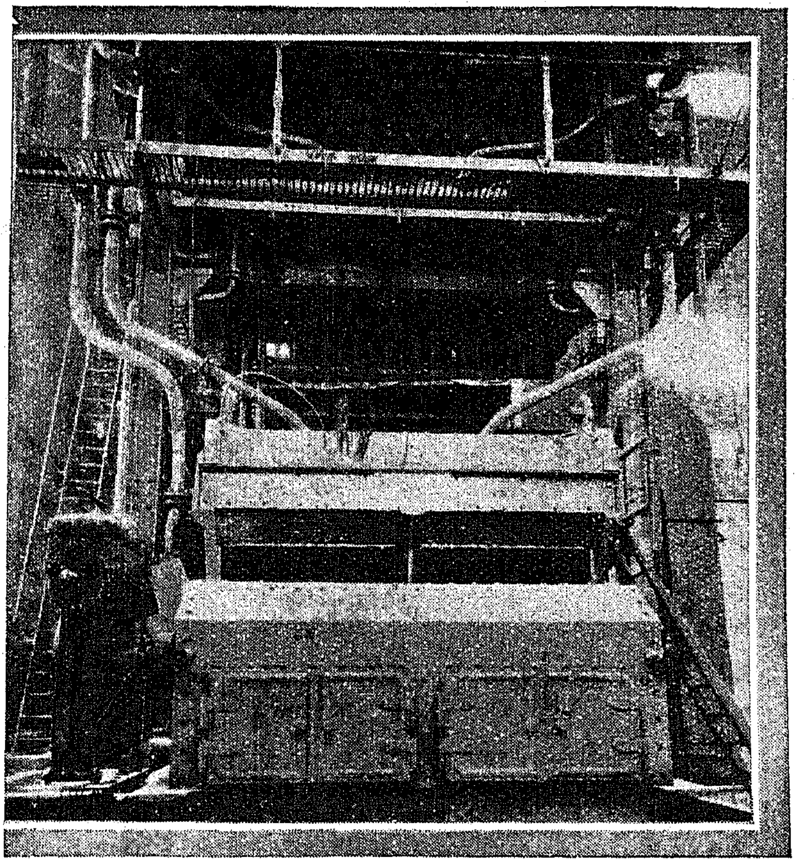

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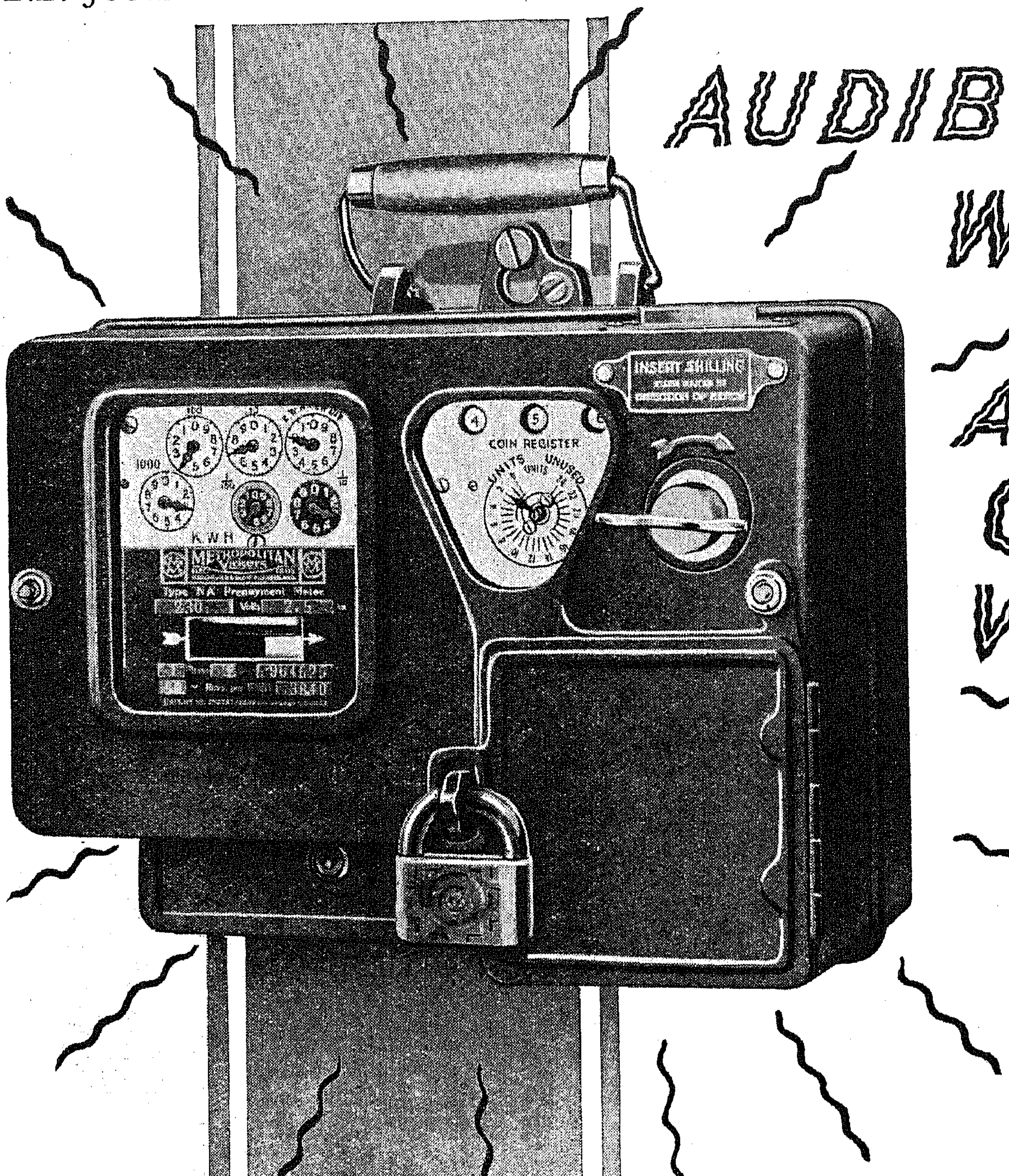

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We have acquired from Thiokol Ltd., of Yardville, New Jersey, the right to manufacture and sell "Thiokol" products under the United Kingdom Patents of Thiokol Ltd.

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THE 36-RANGE UNIVERSAL AVOMETER

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36 RANGES WITH ONE INSTRUMENT

D.C. RANGES			A.C. RANGES	
Current.	Voltage.	Resistance.	Current.	Voltage.
*0-12 amps.	*0-1,200 volts.	*0-1 megohm.	0-12 amps.	0-1,200 volts.
0-6 ,,	0- 600 ,,	*0-100,000 ohms.	0- 6 ,,	0- 600 ,,
*0-1.2 ,,	*0- 120 ,,	*0- 10,000 ,,	0- 1.2 ,,	0- 480 ,,
0- 600 m.a.	0- 60 ,,	*0- 1,000 ,,	0- 0.6 ,,	0- 240 ,,
*0- 120 ,,	*0- 12 ,,		0-120 milliamps.	0- 120 ,,
0- 60 ,,	0- 6 ,,		0- 60 ,,	0- 60 ,,
*0- 12 ,,	*0- 1.2 ,,			0- 12 ,,
0- 6 ,,	0- 600 millivolts.			0- 6 ,,
	*0- 120 ,,			
	0- 60 ,,			

* Indicates the thirteen ranges of the D.C. Avometer.

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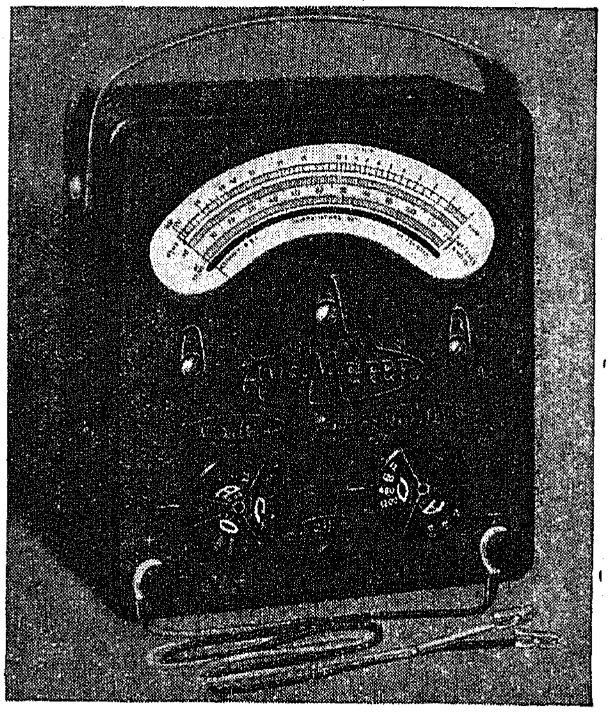
This Book gives a complete survey of radio testing in non-technical language. The testing of all modern valves and every phase of fault-finding are explained in easy phraseology. Numerous diagrams. A Book that meets a long-felt need. **2/6** or post free 2/9



BRITISH MADE

12 GNS.

Also the D.C. Avometer, giving the 13 D.C. ranges indicated by an asterisk. **8** GNS.

Deferred terms if desired.

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A 180-inch single-inlet Keith Mine Ventilating Fan Runner

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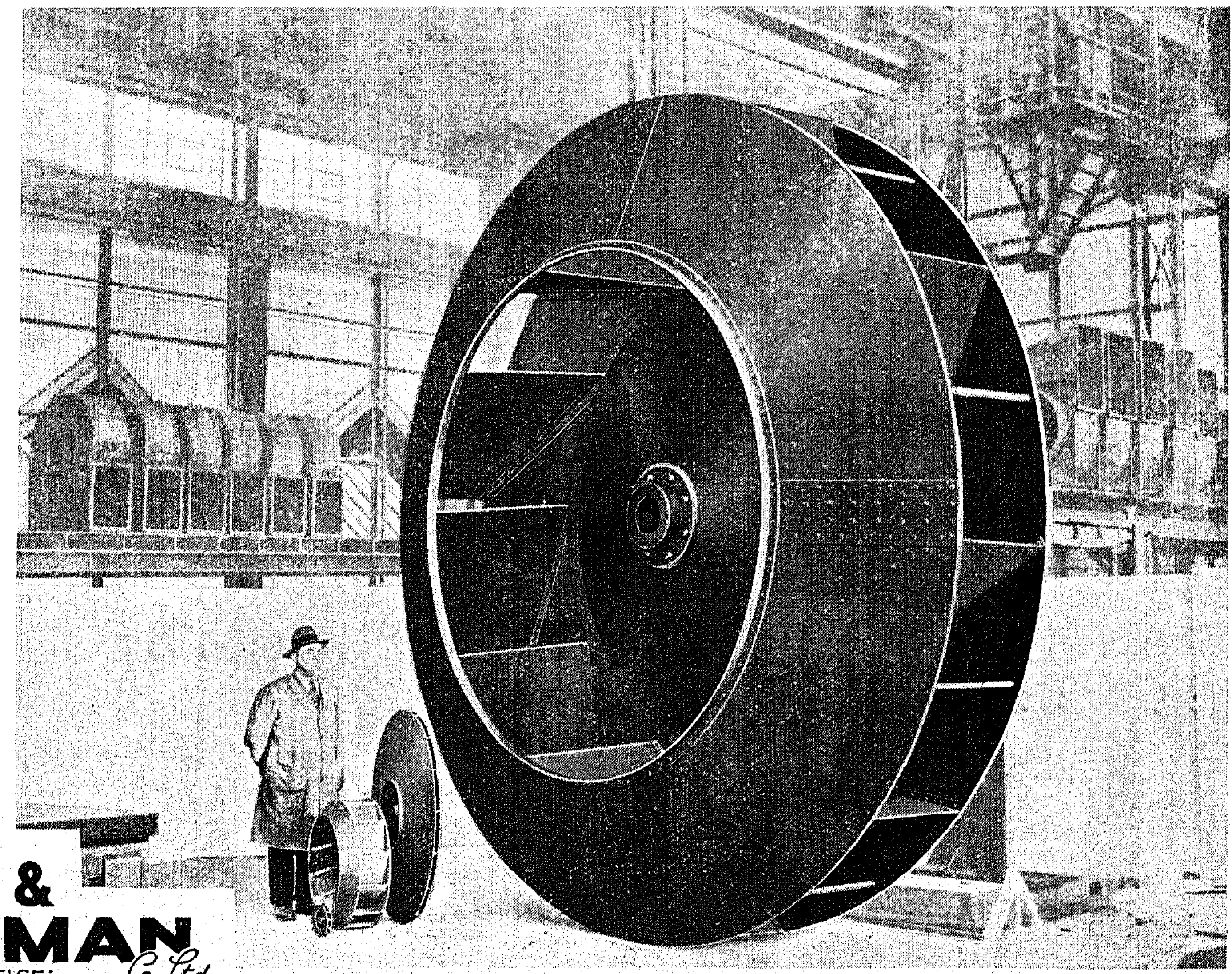

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DUST-PROOF COVERS AND DOUBLE CONTACT RELAYS ENSURE UTMOST RELIABILITY AND LONG LIFE WITH MINIMUM OF ATTENTION

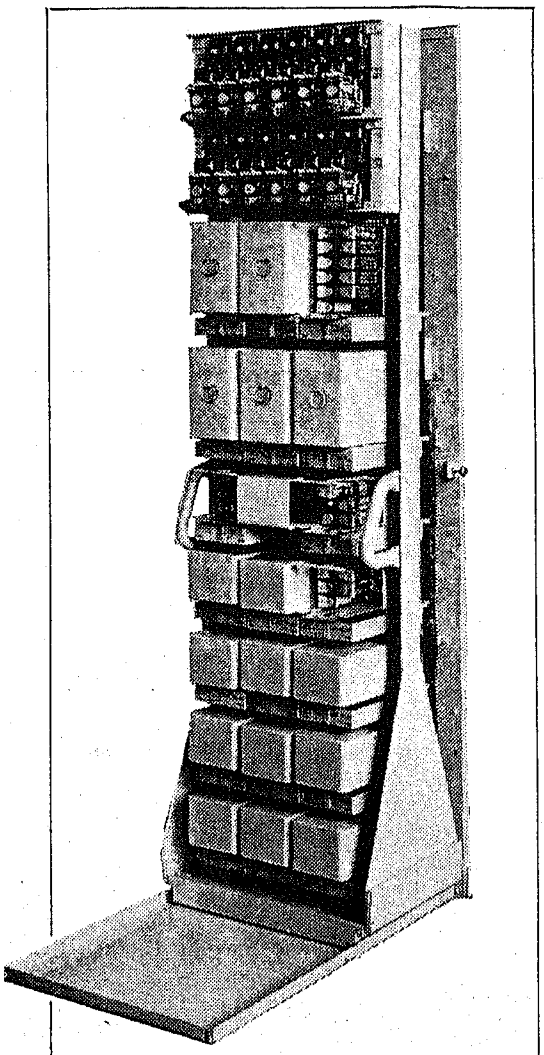
SIMPLEST TO INSTAL, NO SOLDERING REQUIRED

EASILY AND CHEAPLY EXTENDED

CAN BE OPERATED WITHOUT BATTERIES FROM A.C. SUPPLY MAINS

SPECIAL FACILITIES CAN BE PROVIDED

Large numbers of these equipments are now giving good service in all parts of the world.



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5 ft. 5½ ins. × 1 ft. 7 ins. × 1 ft. 4 ins.

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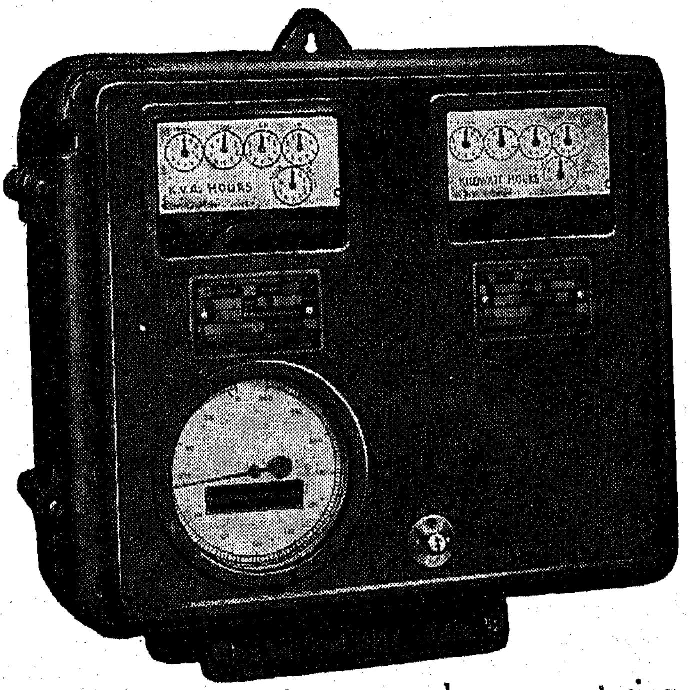
MADE IN ENGLAND



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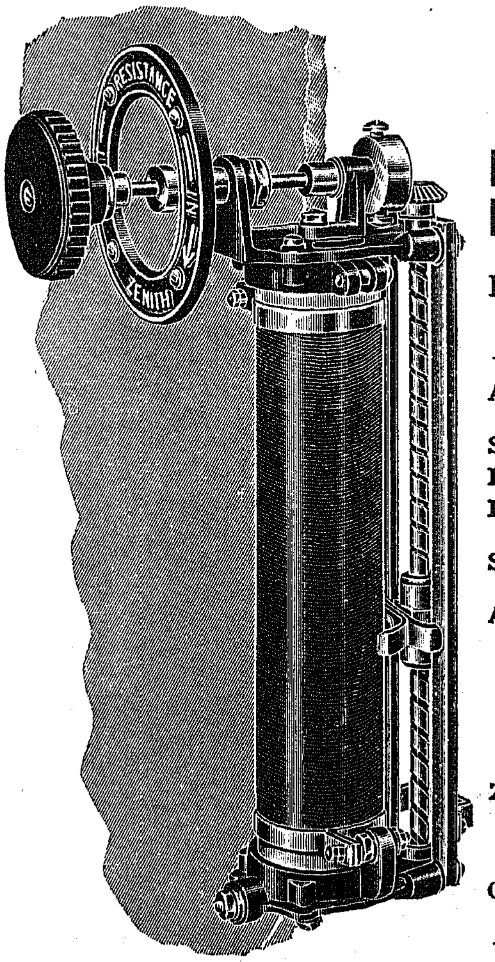

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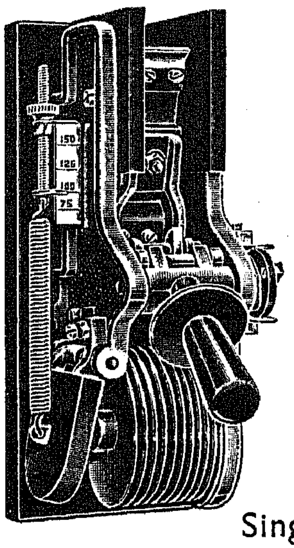

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FOR

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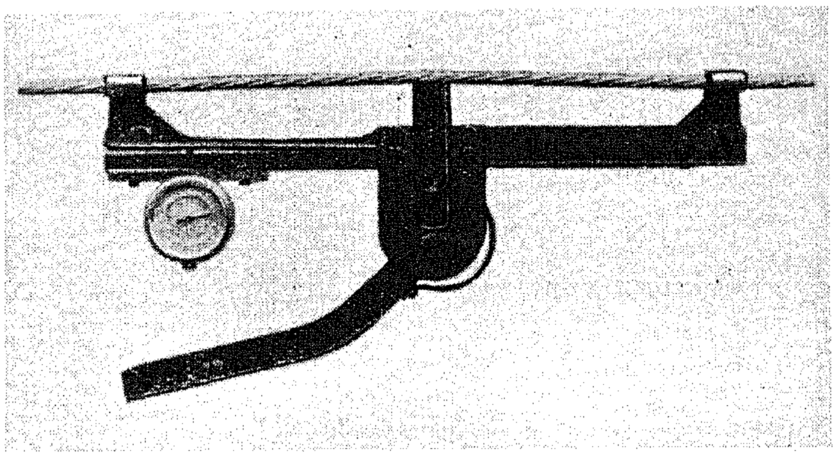
Tension read directly in any required units from calibrated dial.



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The Strand Dynamometer can be provided with a calibrated dial reading directly the tension in any required stranded conductor, stay, or suspension wire, during and after erection, each measurement taking only a few seconds to complete. Calibration charts can, if desired, be provided for additional types of strand. It is of light but strong construction and easily portable in a fitted case.

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